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ABSTRACT

This study presents the development of a continuous wave diffraction radiation oscillator utilizing a sheet electron beam. The oscillator comprises a slow-wave system formed by double-comb gratings, an open resonant cavity consisting of a spherically curved mirror and a cylindrically curved mirror, and a sheet electron beam generated by a diode gun. A permanent magnetic focusing system stabilizes the transmission of the sheet electron beam within the slow-wave system. Through a combination of mechanical and electronic tuning, the oscillator generates stable signal output in the \( \text{TEM}_{00} \) mode. The oscillator’s frequency tuning range spans from 87 to 97 GHz, achieving a maximum output power of 13.5 W.

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I. INTRODUCTION

Microwave vacuum electronics plays a vital role in the generation of high-power radiation sources for various applications, such as radar, radio astronomy, biology, spectroscopy, concealed metal weapon detection, medical imaging, and materials science.\(^1\)–\(^4\) It also provides effective solutions for obtaining high-power terahertz and millimeter-wave signals. Products based on vacuum electronics for millimeter-wave and sub-millimeter-wave applications mainly include traveling wave tubes, klystrons, backward wave oscillators, free electron lasers, gyrotrons, and diffraction radiation oscillators (DROs).\(^1\)\(^1\)\(^2\)

DROs utilize high-Q open resonant cavities as oscillating circuits, effectively addressing the issues of high oscillation mode density and severe mode competition encountered by traditional microwave vacuum electronic devices in high-frequency systems. The device could utilize a comb-like grating as a slow-wave system, fabricated through high-precision mechanical or micro-nano processing techniques. This approach helps alleviate the challenge of processing smaller characteristic sizes of the slow-wave system as the operational frequency of traditional devices increases. Additionally, the wide aspect ratio of the sheet electron beam in the electron optical system enables strong wave-beam interaction. DROs can provide stable oscillation output with low mode competition and high wave-beam interaction efficiency in high-frequency systems, making them highly promising for the development of millimeter-wave and sub-millimeter-wave radiation sources. Many teams worldwide have been working on the development of DROs. Table I summarizes the key parameters of the DROs as reported by current research institutions. It reveals the device’s ability to generate high-frequency output signals, with a maximum frequency of 370 GHz. While the output power in the 8 mm band can reach 60 W in continuous wave (CW) mode, at higher operating frequencies, the device’s output power tends to decrease, often leading the device to operate in pulse mode. Consequently, the development of DROs capable of operating in continuous wave mode at higher frequencies holds great significance for product applications.

V. S. Miroshnichenko from the National Academy of Sciences of Ukraine proposed a theoretical model for a diffraction radiation oscillator with a dual grating high-frequency system.\(^1\)\(^5\)–\(^1\)\(^8\) The goal of the research was to develop a compact, room-temperature operating diffraction radiation source with high output power and spectral purity for applications in plasma diagnostics, electromagnetic wave transmission characteristics, and enhanced dynamic nuclear polarization nuclear magnetic resonance. In collaboration with V. S. Miroshnichenko’s team, the authors of the article successfully developed a diffraction radiation oscillator operating in the W-band based on the theoretical model. This radiation source utilizes a high-performance diode electron gun to generate a high-quality sheet electron beam, and a constant magnetic focusing system ensures stable transmission of the sheet electron beam.
The high-frequency slow-wave system employs a dual grating structure and optimizes the matching between the open resonator and the high-frequency slow-wave system to improve the electron beam utilization efficiency and achieve higher power output. The developed diffraction radiation oscillator holds significant value for the future development of shorter-wavelength millimeter-wave and submillimeter-wave radiation sources.

II. DESIGN OF THE DEVICE

A. High-frequency system

Figure 1 is a schematic diagram illustrating the principle of the high-frequency system of the developed diffraction radiation oscillator. It adopts an open resonant cavity composed of upper and lower mirrors. The upper mirror is a spherical mirror, while the lower mirror is a cylindrical mirror. The slow-wave system consists of two facing comb-like gratings embedded at the central position of the cylindrical mirror, which produces the slow spatial harmonics of the cavity field. The narrow slit formed between the two gratings is the flight path of the electron beam.

![Figure 1: Schematic of the high-frequency system of DRO with double comb gratings.](image)

The oscillator adopts a dual comb-like periodic grating structure, with the tops of the two gratings aligned flush with the surface of the concave mirror. This configuration effectively enhances the field distribution across the sheet electron beam without altering the phase structure of the resonance oscillation field. In addition, diffracted waves escape from the edges of the discontinuous grating and interact with the open resonant cavity, resulting in the formation of a stable high-frequency TEM$_{mnq}$ field between the two mirrors, where m, n, and q denote the mode numbers along the OX, OY, and OZ directions, respectively. At the center of the spherical mirror, a coupling hole with dimensions of 2.54 mm$^2$ is designed, and it is connected to a standard waveguide port through a tapered waveguide to achieve the coupling output of the radiation signal.

According to the Cherenkov radiation synchronization condition, when the electron velocity $V_0$ is close to the phase velocity of the spatial harmonic of the slow-wave system $v_{ph}$, wave–beam interaction occurs between them, resulting in energy exchange. The electron velocity $V_0 = \beta c$, where $\beta$ is the normalized velocity factor of the electron beam with respect to the speed of light $c$. The slow spatial harmonic wave number $k$ of the double grating periodic structure slow-wave system is given by $k = 2 \pi n / L$, where $L$ is the period length of the grating. Electrons interact with one of such harmonics under the synchronization condition

$$\omega \approx k V_0, \quad (1)$$

which leads to a simple relation between radiation wavelength $\lambda$ and structure period $L$

$$\lambda \approx \frac{L}{\beta}, \quad (2)$$

where $\omega$ is the angular frequency of the cavity mode, $\lambda$ is the operating wavelength of the radiated electromagnetic wave in free space.

Therefore, by precisely controlling the flight velocity of electrons in the electron beam and the periodic structural parameters of the comb-grating slow-wave system, it is possible to design electromagnetic waves radiating at specific wavelengths.

This paper presents the design of a diffraction radiation oscillator with a voltage operating range of 0.42–0.45 kV and a central operating frequency of 94 GHz. According to Eq. (2), the period of the grating, L, is approximately 0.41 mm. The resonant matching characteristics

<table>
<thead>
<tr>
<th>Institute</th>
<th>Frequency band (GHz)</th>
<th>Peak power</th>
<th>Operating mode</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAP GYCOM, Russia</td>
<td>90–190</td>
<td>1000–100 mW</td>
<td>Pulse duration &lt; 30 ms</td>
<td>23</td>
</tr>
<tr>
<td>IAP GYCOM, Russia</td>
<td>90–300</td>
<td>500–100 mW</td>
<td>Pulse duration &lt; 10 ms</td>
<td>23</td>
</tr>
<tr>
<td>IAP GYCOM, Russia</td>
<td>140–300</td>
<td>50–30 mW</td>
<td>Pulse duration &lt; 3 ms</td>
<td>23</td>
</tr>
<tr>
<td>IAP GYCOM, Russia</td>
<td>260–370</td>
<td>70–30 mW</td>
<td>Pulse duration &lt; 1 ms</td>
<td>23</td>
</tr>
<tr>
<td>AER, HDL, USA</td>
<td>50–75</td>
<td>5 W</td>
<td>Pulse duration, 40 ps</td>
<td>4</td>
</tr>
<tr>
<td>IRE, Ukraine</td>
<td>31–37</td>
<td>60 W</td>
<td>CW</td>
<td>4</td>
</tr>
<tr>
<td>IRE, Ukraine</td>
<td>28–32</td>
<td>30 W</td>
<td>CW</td>
<td>4</td>
</tr>
<tr>
<td>IRE, Ukraine</td>
<td>47–63</td>
<td>4 W</td>
<td>CW</td>
<td>4</td>
</tr>
</tbody>
</table>

*IP represents the Institute of Applied Physics of the Russian Academy of Sciences.

*HDL stand for the U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories.

*IRE refers to the Usikov Institute for Radio Physics and Electronics of Ukraine.
between the grating resonant cavity and the open resonant cavity depend on the depth, b, of the cavity, which can be calculated using the formula $b \approx \frac{(2m+1)\lambda}{4}$, where $m = 1, 2, 3$, and $\lambda$ is the wavelength of the TEM$_{00q}$ wave mode in the two-dimensional waveguide (grating resonant cavity). In this device, the depth of the cavity, $b$, is set to 4 mm. To achieve full phase matching with the open resonant cavity, the parameters of the dual grating need to satisfy the following condition:\(^{15}\)

$$f = \frac{c}{2b} \sqrt{1 - \frac{2b^2}{\lambda_{cr}}},$$

(3)

where $\lambda_{cr}$ is the cutoff wavelength of the rectangular waveguide $H_{10}$ mode with dimensions $d \times a$ in the schematic diagram. Taking into account the influence of the electron beam channel, the cutoff wavelength of this rectangular waveguide should be slightly smaller than $2a$, and in this paper, $\lambda_{cr}$ is chosen as 1.98a. With a device operating frequency of $f = 94 \text{ GHz}$ and a depth of $b = 4 \text{ mm}$, we obtain $\lambda_{cr} = 1.98a = 3.47 \text{ mm}$. Considering the influence of the electron beam transverse size and electron transmission rate in the electron optical system, the electron beam channel width of the device $\delta$ is set to 0.15 mm, resulting in a cavity depth of $h = 0.79 \text{ mm}$ and a width of $a = 1.74 \text{ mm}$.

Designing the curvature radius of the upper spherical mirror as 110 mm and the curvature radius of the lower cylindrical mirror as 80 mm, while ensuring the stability condition of the resonant cavity. For the TEM$_{00q}$ oscillation mode on a hemispherical resonant cavity, the spot radius $w_0$ formed on the cylindrical mirror can be determined by the following equation:\(^{23}\)

$$w_0 = \frac{\lambda}{\pi} \sqrt{D(R_{ph} - D)},$$

(4)

where $D$ is the distance between the mirrors, and $R_{ph}$ is the curvature radius of the spherical mirror.

On the spherical mirror, the spot radius $w_{c\phi}$ can be determined by the following equation:

$$w_{c\phi} = \frac{\lambda}{\pi} R_{c\phi} \sqrt{\frac{D}{R_{c\phi} - D}},$$

(5)

where $R_{c\phi}$ represents the curvature radius of the spherical mirror.

According to formulas (4) and (5), we can obtain the spot information formed on the spherical mirror and cylindrical mirror for the open resonator mentioned in the paper, as shown in Fig. 2. To reduce the level of radiation losses in the open resonant system, it is recommended to design the length of the interaction space in the diffraction radiation oscillator to be 1.5 to 2 times the diameter of the spot. Additionally, if the mirror size of the resonant system is too large, it will increase the size and weight of the electron optical system’s focusing magnetic system. Considering all factors, we have designed the length of the interaction space in the diffraction radiation oscillator as $L = 15 \text{ mm}$.

By installing a vacuum dynamic sealing system above the spherical mirror, the distance $D$ between the mirror surfaces can be changed, allowing for variations in the resonant field along the longitudinal axis of the open resonant cavity. This can excite oscillations of various TEM$_{pq}$ modes. As shown in Fig. 3, oscillations of TEM$_{003}$, TEM$_{006}$, TEM$_{007}$, and TEM$_{008}$ modes can be excited when the distance between the mirrors is 7.957, 9.555, 11.247, and 17.710 mm, respectively.

Finally, through optimization using three-dimensional electromagnetic simulation software Microwave Studio (MWS), the structural parameters of the high-frequency system are obtained, as shown in Table II. The slow-wave structure (SWS) grating for this project is manufactured using wire electrical discharge machining (WEDM). The surface roughness (Ra) of the grating is below 1.6 $\mu$m, and the manufacturing tolerance is less than 0.005 mm. The assembly tolerance between the electron gun and the SWS is less than 0.015 mm.

### B. The electron optics system

A diode-type electron gun is adopted to generate the sheet electron beam required by the device. Figure 4 shows the schematic diagram of the electron gun, the working voltage of which can reach 5 kV. The cathode is prepared using barium tungsten material independently developed by our team, and its optimum working temperature is about 1050°C. The emission current of the electron gun can be changed by changing the acceleration voltage and the working temperature of the cathode. When the size of the cathode emitting surface is $3.6 \times 0.1 \text{ mm}^2$, experimental results show that the emission current of the electron gun can reach 150 mA, corresponding to an emission current density of 41.6 A/cm$^2$.

Since the diffraction radiation oscillator of this paper works in the millimeter-wave band, the amplitude of the synchronous harmonic decreases with the increase in the distance from the surface of the periodic structure. Its scale is given by the following formula:\(^{25}\)

$$\Lambda = \frac{L}{2\pi} = \frac{\beta R}{2\pi}.$$  

(6)

In order to increase the electron efficiency and total output power of the device, it is necessary to minimize the distance between the sheet electron beam and the high-frequency slow-wave system’s surface as much as possible, while ensuring that the electron beam can stably transmit over a distance of more than 15 mm beyond the grid length to increase the interaction time between the electron beam and the high-frequency slow-wave system. Therefore, it is necessary to use a
TABLE II. The parameters of the high-frequency system.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grating period, $L$</td>
<td>0.4 mm</td>
<td>Channel width, $\delta$</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>Grating depth, $h$</td>
<td>0.78 mm</td>
<td>Grating slot width, $d$</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>Grating thickness, $b$</td>
<td>4.0 mm</td>
<td>The width of the resonant, $a$</td>
<td>1.72 mm</td>
</tr>
<tr>
<td>Grating length</td>
<td>15 mm</td>
<td>Radius of cylindrical mirror, $R_{cyl}$</td>
<td>80 mm</td>
</tr>
<tr>
<td>Radius of spherical mirror, $R_{sph}$</td>
<td>110 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIG. 3. The vibration modes inside the resonant cavity at different mirror distances: TEM$_{005}$ at 7.957 mm (a), TEM$_{006}$ at 9.555 mm (b), TEM$_{007}$ at 11.247 mm (c), and TEM$_{008}$ at 12.710 mm (d).

FIG. 4. The simulation results of electron beam generation by the electron gun.

FIG. 5. The schematic diagram of the MFS (a) and the distribution of magnetic field magnitude (b).
permanent magnet focusing system (MFS) to magnetically confine the electron beam. Theoretical simulations and experimental results indicate that a uniform magnetic field exceeding 0.5 T is sufficient to ensure the stable transmission of the electron beam in this study. The theoretical model of the MFS designed in this paper is shown in Fig. 5(a). The magnetic system consists of two magnetic rings, every ring is formed from 8 poles, the inner and outer radius of the magnetic rings are 44 and 130 mm, respectively, and the thickness of the magnetic rings is 36 mm. The magnetic rings are made of neodymium iron boron material, the residual magnetic strength is 1.13 T, and the coercivity is 836 kA/m. The magnetization direction of one of the magnetic rings is from the inside to the outside, and the magnetization direction of the other magnetic ring is from the outside to the inside. A magnetic field concentrator made of pure iron is formed at the center of the two magnetic rings. Outside the magnetic rings, a positioning fixture made of pure iron ensures that the distance between the two magnetic rings is maintained at 42 mm.

The minimum magnetic field along the central axis in the y-direction is situated at the center position of the symmetry axis, with a measured magnetic field intensity $B_y$ of 0.66 T. As illustrated in Fig. 5(b), the four curves depict the measured magnetic field intensities within planes perpendicular to the Y-axis. The center points of the planes are designated as a (0, 0, 0), b (0, 3 mm, 0), c (0, 6 mm, 0), and d (0, 9 mm, 0). It is evident that in the vicinity of the symmetry centerline of the MFS Y-axis, the magnetic field intensity undergoes minimal variation, resulting in the formation of a near-uniform region. The radius of this uniform area exceeds 3 mm, surpassing the cross-sectional dimension of the electron beam in this study, thereby facilitating the long-distance transmission of the sheet electron beam. We investigated the transmission characteristics of the sheet electron beam under the influence of the MFS. It was observed that, due to the interaction between the slow-wave system and the electron beam, the electron throughput rate exceeds 90%.

C. Particle-in-cell (PIC) results

The working properties of the DRO are simulated using the three-dimensional fully electromagnetic particle-in-cell (PIC) code UNIPIC-3D, which solves the relativistic Newton–Lorentz force equation and Maxwell’s equations on conformal meshes and includes distributed loss on the device walls. The sheet electron beam accelerating voltage was set to 4.3 kV, and the current was 150 mA, with a cross section of $3.6 \times 0.1 \text{ mm}^2$. The simulated output power vs time (a), working frequency (b), phase space of electrons (c), the TEM$_{007}$ radiated mode of the device in the Y–Z plane (d), and X–Z plane (e).

FIG. 7. Photograph of the fabricated diffraction radiation oscillator.
A distance of 11.247 mm was set between the two mirrors. In Fig. 6(a), the DRO output signal is shown. The electron output signal tended to stabilize for simulation times longer than 8.7 ns, with a pulse power exceeding 20 W and an average power of around 11 W. Figure 6(b) presents the output signal frequency, which measured 94.3 GHz, without any other noticeable spurious signals after performing a Fourier transform on the simulated output signal. Figure 6(c) showcases the electron’s phase space distribution information, illustrating the conversion of the electron beam’s electrical energy into electromagnetic wave energy at different locations. Additionally, Figs. 6(d) and 6(e) display the TEM₀₀₇ radiated mode of the device in the Y–Z plane and X–Z plane, respectively, obtained during hot test simulation. Similarly, radiative behaviors are observed for varying mirror separations.

III. EXPERIMENTAL RESULTS

The corresponding diffraction radiation oscillator (DRO) has been fabricated, and the physical photo is presented in Fig. 7. The assembling process of the whole device employs resistance welding and argon arc welding. The dimensions of the device are Φ 130 × 130 mm², and its inner vacuum is pumped to above 2.0 × 10⁻⁷ Pa by a turbo molecular pump.

We carried out hot testing on the developed DRO and analyzed its output parameters using a power meter and a spectrum analyzer. Figure 8(a) illustrates the mechanical tuning performance of the DRO, displaying the frequency output at various mirror spacings. The solid line represents the theoretical values, while the solid dots represent the actual test results. It is evident that the DRO’s frequency output range spans from 87 to 97 GHz. Taking assembly and measurement errors into account, it is apparent that the DRO can work in the fundamental mode (TEM₀₀₅ to TEM₀₀₉). Moreover, the device’s output frequency closely corresponds to the distance between the two mirrors as demonstrated in the preceding simulation results.

Figure 8(b) shows the electronic tunability of the DRO device operating in the TEM₀₀₇ mode with an electron beam current of 90 mA. By varying the acceleration voltage of the electron beam, both the output power and oscillation frequency of the oscillator are altered. It is evident that the oscillation frequency of the device demonstrates a roughly linear relationship with the acceleration voltage of the electron beam, with a slope of approximately 0.67 MHz/V.

Figure 9 illustrates the changes in output power and frequency of the DRO in TEM₀₀₇ and TEM₀₀₈ modes as a function of the mirror spacing, with a cathode current (I₉) of 100 mA. In the TEM₀₀₇ mode, the DRO exhibits an output frequency range of 90.2–95.1 GHz. As the
mirror spacing decreases, the oscillation frequency of the DRO increases correspondingly. Similarly, in the TEM\textsubscript{008} mode, as the mirror spacing decreases, the oscillation frequency of the DRO also rises, resulting in a frequency output range of 90.8–96.2 GHz. In the TEM\textsubscript{007} mode, the maximum continuous wave output power reaches 8.0 W at a frequency of 93.2 GHz.

During the testing of the device, it was noted that the device exhibits a relatively higher startup current at the edge of the oscillation region, while the startup current is comparatively lower in the central region of the operating mode. Specifically, in the TEM\textsubscript{007} mode, the startup current ranges from 18 to 33 mA, whereas in the TEM\textsubscript{008} mode, the startup current varies between 19.6 and 51 mA. In summary, the startup current of the DRO in the TEM\textsubscript{008} mode is greater than that in the TEM\textsubscript{007} mode.

Figure 10(a) illustrates the relationship between output power and cathode current for the device operating in the TEM\textsubscript{005} mode, with an electron acceleration voltage of 4.3 kV and a mirror spacing (D) of 8.2 mm in the open resonator. The output power of the oscillator shows a linear increase with the rise in cathode current. Upon reaching a cathode current of 135 mA, the output power reaches its peak at 13.5 W. Concurrently, the overall efficiency of the device rises with the increasing cathode current, attaining a maximum value of around 2.3%.

Figure 10(b) shows the output spectrum of the DRO under the given electron acceleration voltage and resonator parameters. The strongest peak is located at 93.33 GHz. Due to the high-Q value of the open resonator and the stable power supply system, the frequency full width at half maximum (FWHM) of the device is 12 kHz, and the frequency stability is approximately 0.13 ppm.

IV. CONCLUSIONS

This study presents a DRO utilizing a dual-grating slow-wave structure. By adjusting the distance between the open resonator mirrors, various TEM\textsubscript{00q} oscillation modes can be achieved within the resonator, leading to stable signal output. The device offers electron tuning capabilities, allowing for different electron output frequencies by adjusting the accelerating voltage of the electron beam, within a tuning range of 87–97 GHz. The electron optical system of the DRO consists of a diode-type electron gun and a constant magnetic focusing system. The maximum output power of the DRO is 13.5 W in CW mode, with an output signal FWHM of 12 kHz and a frequency stability of approximately 0.13 ppm. The packaged diffraction radiation oscillator has a weight of less than 3 kg. The development of this DRO holds significant implications for the advancement of higher frequency and higher power DROs.

ACKNOWLEDGMENTS

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Hongzhu Xi: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Writing – original draft (equal). Minjian Huang: Software (equal); Writing – review & editing (equal). Pengkang Wang: Funding acquisition (equal); Investigation (equal); Methodology (equal). Jie Shu: Resources (equal); Software (equal); Supervision (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES