Progress in Theoretical Design and Numerical Simulation of High Power Terahertz Backward Wave Oscillator

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Abstract—Results of theoretical analysis and numerical simulation studies of a MW-class, overmoded terahertz oscillator are presented. The device consists of a large diameter cross-section, slow wave structure with a unique profile of wall radius specifically designed to support surface wave and to provide a strong beam-wave coupling at a moderate voltage. Under the condition of 500 kV voltage and 2 kA beam current, the 2.5-D particle-in-cell simulation predicted the output power of 41 MW at the frequency of 0.143 THz. And an efficiency of 4.1\% was also obtained with a perfect time plot and fine spectrum characteristic.

1. INTRODUCTION

“Terahertz (THz) fields” is a generic term for electromagnetic waves within a spectrum between 0.1 and 10 THz. The interest in this frequency range is fuelled by the fact that this range of frequency is the place where unique physical phenomena with characteristic features are produced [1]. For example, the spectral energy distribution in observable galaxies shows that 50\% of the total luminosity are located in the THz frequency range. And THz signals are the information carriers in the ultra wideband communications systems, which are developed now and are expected to become a commercial reality in the next decade.

However, due to the difficulties in generation and detection of the Terahertz signals, they were until recently an almost unexplored area of research. The developments of ultra fast optical techniques, the manufacturing of semi-insulating semiconductors and the micromachining of vacuum electron devices have boosted the terahertz fields as a new research area [2]. This paper presented the recent results of design and simulation of 0.14 THz high power relativistic backward wave oscillator (BWO) in our laboratory.

2. GENERAL CONSIDERATIONS

2.1. Overmoded Slow Wave Structure (SWS)

The main function of SWS in the BWO is to support slow waves with the phase velocity below that of the light, and to ensure strong enough coupling impedance over the frequency range of interest for an electron beam located relatively far from the structure’s inner surface. In order to meet these requirements, various axial profiles of wall radius for the periodic structure were analyzed, such as sinusoidal, rectangular, trapezoidal and semicircular. And finally a spatially periodic structure

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{(a) 3-D SWS model with rectangular rippled wall, (b) 2-D axial symmetric cross-section of the SWS}
\end{figure}
with the rectangular profile was chosen because it can meet the both requirements (slow wave and strong coupling) and supply the fabrication convenience in the millimeter dimensional range. The model of the selected structure is illustrated in Fig. 1.

In this structure, the transverse diameter \( D(D = 2R) \) is designed to several times the free-space wavelength \( \lambda \) thereby reducing the internal field stress for the same power flow, and in other words it can increase the power-handling capacities of the high power terahertz devices [3]. For a TM01 mode propagating in the selected SWS, an approximate relation between the maximum power \( P_{\text{max}} \) and the maximum strength of electric field allowable at the wall, \( E_{\text{max}} \), can be given by

\[
P_{\text{max}} = 8.707 \left( \frac{E_{\text{max}} \cdot \lambda}{511} \right)^2 \pi^2 \sigma^4 \sqrt{1 - \left( \frac{\nu_{0,1}}{2\pi D'} \right)^2} \frac{1}{\nu_{0,1}}
\]

where \( D' = \pi D/\lambda, \) \( \lambda \) is the free-space wavelength, \( \nu_{0,1} \) is the first root of equation: \( J_0(x) = 0, \) \( J_0(x) \) is the Bessel function of order 0. From the formula (1), we can find that the output power \( P_{\text{max}} \) is dramatically increased with the enlargement of transverse diameter \( D \). And if \( D/\lambda \geq 1.76, \) the SWS is defined as an overmoded SWS.

2.2. Surface Wave Operation

Linear beam relativistic BWOs are based on the interaction between an electron beam and the electromagnetic field containing slow-wave components. Such a field can be realized in the spatial periodic structure where the electromagnetic field at an eigenfrequency \( \omega \) can be expressed as an

![Figure 2](image-url)
infinite sum of spatial harmonics:

\[ E_z = \sum_{n=-\infty}^{+\infty} a_n G_0 (k_{c,n} r) e^{j k_{c,n} z} e^{-j \omega t} + c.c \]  (2)

where

\[ k_{c,n} = k_{c,0} + \frac{2\pi n}{L}, \quad n = 0, \pm 1, \pm 2, \ldots \]

\( L \) is the spatial period of the SWS, \( n \) is the spatial harmonics number. And the transverse and longitude wave numbers satisfy the equation

\[ k_{c,n}^2 + k_{z,n}^2 = \left( \frac{\omega}{c} \right)^2 \]  (3)

If \( |k_{z,n}| < \frac{\omega}{c} \), the spatial harmonic is fast and volumetric since its field profile is described by the ordinary Bessel function, \( G_0 = J_0 \). However, when \( |k_{z,n}| < \frac{\omega}{c} \), the harmonic is slow, and the field profile is described by the modified Bessel function, i.e., \( G_0 = I_0 \). The field of this harmonic has the characteristic that the field is mainly localized near the surface of SWS, which is defined as surface wave. Our goal is to design this kind of SWS for which the eigenmode in a certain frequency range consist of only slow spatial harmonics, which will play an important role in the realization of high power overmoded THz wave sources.

3. DISPERSION RELATION OF SWS

Dispersion diagrams, to some extent, are the most important characteristic of SWS. From the diagrams, the operation frequency of device can be approximately determined, and the other eigenvalues such as coupling impedance and linear growth rate can also be derived as well [4]. We investigated the dispersion relation of SWS with various dimensional parameters. And the dependence of the dispersion characteristics on these parameters is showed in Fig. 2. It is apparent that the frequency of interest (0.14 THz) is included in the frequency range of the SWS. From the calculated diagrams, we can also preliminary determine the values of dimensional parameters of SWS as well as the acceleration voltage of the electron beam in order to ensure the device operate at the frequency of 0.14 THz.

4. PARETICLE-IN-CELL (PIC) SIMULATION AND RESULT ANNALSIS

The analytic theory of the microwave electronics can provide an exact description of the normal modes of the SWS in the absence of a beam. Also, it supplies us with an accurate picture of small-amplitude behavior when the beam is added to the system. However, in the regime of large-amplitude, nonlinear operation as the situation investigated in this paper, the PIC computer simulations should be used in order to examine the behavior of the THz BWO [5]. The simulation model is illustrated in Fig. 3, and the values of parameters are given in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( R_a )</th>
<th>( L )</th>
<th>( d )</th>
<th>( a )</th>
<th>( D_1 )</th>
<th>( D_2 )</th>
<th>( H )</th>
<th>( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>3.0 mm</td>
<td>0.9 mm</td>
<td>0.4 mm</td>
<td>0.2 mm</td>
<td>4.0 mm</td>
<td>4.0 mm</td>
<td>1.0 mm</td>
<td>20</td>
</tr>
</tbody>
</table>

The simulation was carried out with the boundary conditions that the waveguide wall is a perfect conductor, that there was an axial symmetry of \( z \) axis, and that the electromagnetic waves were outgoing at the ends of the structure to a good approximation. As the initial condition for the simulation, there were no electromagnetic fields in the SWS, and the electron beam was just incident at the left-end side of the structure. Under the condition of 500 kV voltage, 2 kA beam current and 4T axial guiding magnetic field, the oscillator began to work. Fig. 4 shows the temporal behavior of typical field component at a certain point in the SWS and the corresponding Fourier transform of this signal. We can find that the oscillator steadily operated at the frequency of 0.143 THz. The time plot of the output power is indicated in Fig. 5. And the peak power of 41 MW (efficiency equals to 4.1%) was obtained from the device. Fig. 6 exhibits the distribution of longitude electric field
Figure 3: THz BWO model in the PIC simulation.

Figure 4: (a) Time plot of the generated signal, (b) spectrum of the generated signal.

$E_Z$ along the radial direction at the coordinate of $z = 5 \text{mm}$. It is found that the field decreased along the given radius from the inner surface of the SWS to the center axis, that is to say, the field accumulated almost near the inner surface, which confirmed that the system we designed operated as a surface wave oscillator.

Figure 5: Time plot of the output power.

Figure 6: Distribution of $E_Z$ along the radius.
5. CONCLUSIONS
In this paper, we presented the preliminary research progress on the overmoded, MW class terahertz source in our lab. It was found that an overmoded interaction SWS must support surface wave that are synchronous with the electron beam, and simultaneously exhibit large values of the coupling impedance. The dispersion characteristics of the SWS with periodic rectangular rippled-wall were examined. And a set of optimal values of the system parameters were specified. With the 2.5-D particle-in-cell simulation method, the power level of 41 MW and the efficiency of 4.1% were obtained at the frequency of 0.14 THz. Further innovation of the device structure is required in order to enable the generation of higher wave power at higher frequencies.

REFERENCES