Vacuum Electron Tubes for THz Applications

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Abstract

Vacuum devices, such as TWTs and BWOs, for THz regime, represent a new challenge in vacuum electronics. Structures with dimensions in the range of microns are required to optimize the energy transfer from an electron beam to the RF field. The availability of codes to accurately analyze micro slow-wave structures at THz frequency is fundamental for a reliable and fast design.
A procedure to design a THz backward-wave oscillator based on an analytical code to compute the cold parameters in backward-wave mode and 3-D electromagnetic codes for device performance is presented. An output power of 190 mW is demonstrated at 1027 GHz.

1. Introduction

The availability of electron devices in sub-millimeter wavelength and THz frequency range would enable numerous applications in the field of security, medicine, material science and imaging that require powerful, portable, compact and lightweight devices. Vacuum electron tubes represent the solution to provide high RF power at THz frequencies. The formidable task of operating in a frequency range that lies between microwave and optical region requires stressing the technology over its limits and unconventional approaches [1, 2].

A vacuum traveling wave tube consists of an electron gun generating an electron beam interacting with a slowed RF signal along a slow-wave structure (SWS). Slow-wave structures with dimensions in the range of tens of microns, with metal surface finishing in the order of tens of nanometers, are required to optimize the energy transfer from the electron beam to a THz RF field. The availability of analysis tools for a fast and accurate characterization both of the SWS structures and the interaction with the electron beam, in THz frequency range, is fundamental for the success of the realization.

The introduction of three-dimensional electromagnetic simulators has highly enhanced the flexibility and the accuracy of the design, but, even if more and more powerful computers are available, the huge mathematical complexity represents a formidable and time computing task.

Analytical methods maintain their validity as fast and accurate tools, especially in the first design phase where the design choices have to be defined. The validation of analytical methods by 3-D EM simulator is a viable solution to merge high accuracy with short computing time.

Corrugated rectangular waveguide are suitable as SWS at THz frequencies, due to easy fabrication by high-aspect ratio processes such as DRIE (deep reactive ion etching), LIGA (German acronym of lithography, electroplating and molding) or UV/SU-8 lithography. The cold parameters of the corrugated waveguide SWS (phase velocity, interaction impedance) determine the proper interaction characteristics with the electron beam and have to be computed accurately [3-5].

In this paper the model for dispersion and interaction impedance in backward wave mode and its application, together with 3-D electromagnetic and particle-in-cells simulators, in the design of backward wave oscillators in THz frequency range will be described.

2. Analytical computation of the cold parameters

The field expansion in [3] is used to compute the dispersion equation and the backward wave interaction impedance of a corrugated waveguide. The importance of having an expression for the interaction impedance in backward wave mode is in the proper choice of the beam voltage and dimensions for an effective interaction and in the evaluation of the tuning properties of a backward wave oscillator. The schematic of the corrugated waveguide is shown in Fig.1.

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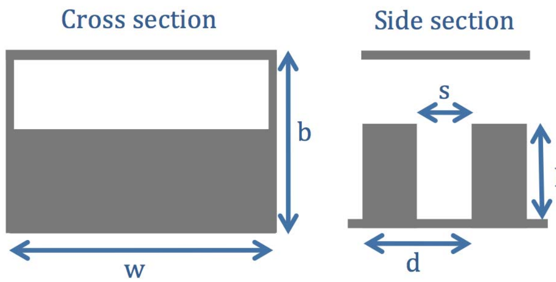

Fig.1 Schematic of the corrugated waveguide and dimensions

Table I

Parameter	Dimension (m)
p	60
b	110
s	25
d	50
w	240
Beam distance δ	15
Beam width	80
Beam thickness	20

The dispersion equation is [3]:

$$D(\omega,k_z) = 1 - \frac{s}{d}\,\tanh(\nu_x\,p)\,\sum_m \frac{\nu_x}{\nu_m}\,\frac{\mathrm{sinc}^2(k_{z\,m}\,\frac{s}{2})}{\tanh\left[\nu_m\,(b-p)\right]} \tag{1}$$

where

$$k_{z\,i} = k_z + \frac{2\pi\,i}{d}\,;\quad k_x = \frac{\pi}{w}\,;\quad \nu_x = \sqrt{k_o^2 - k_x^2}\,;\quad \nu_i = \sqrt{k_{z\,i}^2 + k_x^2 - k_o^2}$$

and w is the width of the waveguide; $k_{z\,i}$ is the longitudinal wavenumber of the i-th space harmonic.

The interaction impedance of the n-th space harmonic is defined as:

$$K_p^{(n)} = \frac{\left|E_z^{(n)}\right|^2}{2\,\beta_{z\,(n)}^2\,\Pi} \tag{2}$$

where $E_z^{(n)}$ is the z-component of the electric field, $\beta_{z(n)}$ is the propagation constant and Π is the power of the propagating field. An expression of Π is obtained by computing the Poynting vector flux and taking into account all the space harmonics of the electromagnetic field:

$$\Pi = \frac{\omega\mu_o\,w\,(b-p)}{8\,\nu_x^2}\,\sum_m \left|A_m\right|^2\,k_{z\,m}\,\left[1 + \frac{\sinh\left[2\,\nu_m\,(b-p)\right]}{2\,\nu_m\,(b-p)}\right] \tag{3}$$

where:

$$A_n = B_o\,\frac{s}{d}\,\frac{\nu_x}{\nu_n}\,\frac{\sin(\nu_x\,p)}{\sinh\left[\nu_n\,(b-p)\right]}\,\mathrm{sinc}\left(k_{z\,n}\,\tfrac{s}{2}\right)\,e^{-jk_{z\,n}\,\frac{s}{2}} \tag{4}$$

B_o is an amplitude factor. After some calculations results:

$$K_p^{(n)}(x,y) = \frac{4}{w\,(b-p)}\,\frac{\nu_o^2}{k_{z\,n}^2}\,\frac{\omega\ ,\mu}{\nu_x^2}\,\frac{A_n^2\,\sin^2(k_x\,x)\,\sinh^2\left[\nu_n\,(b-y)\right]}{\sum_m \left|A_m\right|^2\,k_{z\,m}\,\left[1 + \frac{\sinh[2\,\nu_m\,(b-p)]}{2\,\nu_m\,(b-p)}\right]} \tag{5}$$

In backward wave regime the harmonic n = -1 is considered.

The good agreement in comparison with an eigenmode 3-D electromagnetic simulator (CST-MWS) for backward wave regime (n = -1 harmonic) demonstrates the validity of the method (Fig.2).

The corrugated waveguide SWS effectively support the interaction with a beam of rectangular section (sheet beam). The analytical expression for the interaction impedance (5) permits to evaluate the region over the corrugation for the best interaction with a sheet electron beam. In Fig.3 it is shown the behavior of K_p as a function of x and y coordinates, assuming the dimensions in Table I and 12 kV beam voltage (corresponding to 1027 GHz). It can be seen that the region useful for a good interaction with an electron beam is limited to the central region, very close to the corrugation edge.

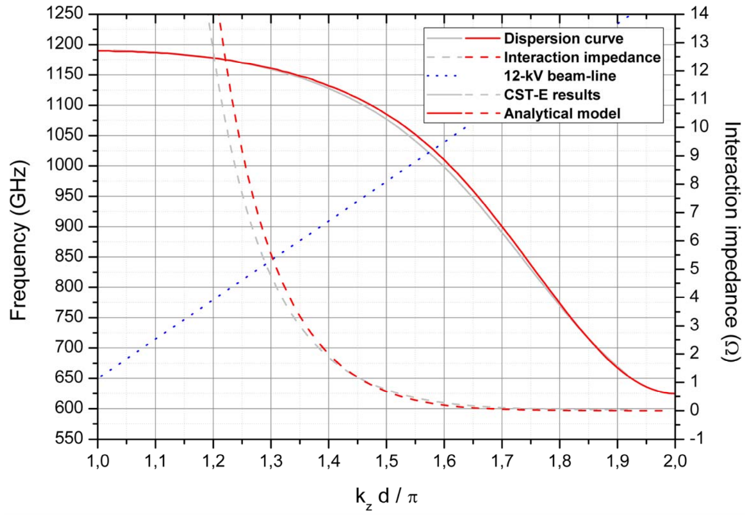

Fig.2 Dispersion curve and interaction impedance for the backward wave mode.

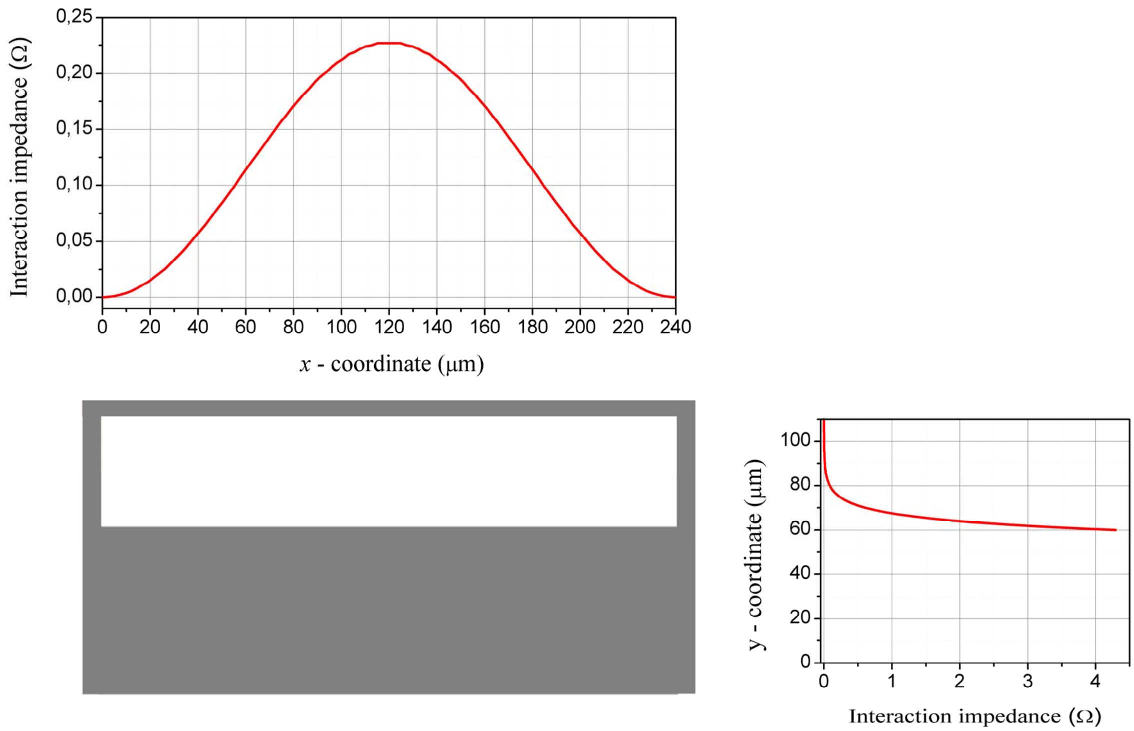

Fig.3 Distribution of the interaction impedance (n=-1) as a function of x and y coordinates.

3. 1-THz Backward wave oscillator

A backward wave oscillator based on a corrugated rectangular waveguide is designed and simulated. The first step is to design and optimize the corrugated waveguide SWS (Fig. 1), by the presented analytical model, to get the required central operating frequency at about 1 THz. The dimensions of the corrugated waveguide SWS are reported in Table I. The dimensions are in the range of high-aspect ratio micro-fabrication processes.
A beam voltage of 12kV is chosen to cross the interaction impedance curve in its central region. This corresponds to an operating frequency of 1.027 THz (Fig.2) and assures a wide tuning range.

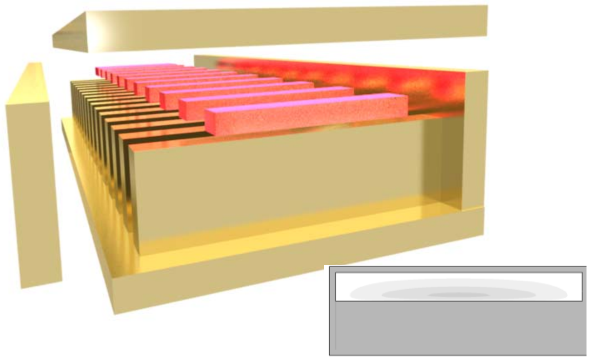

Fig.4 Corrugated waveguide SWS with electron beam and field distribution.

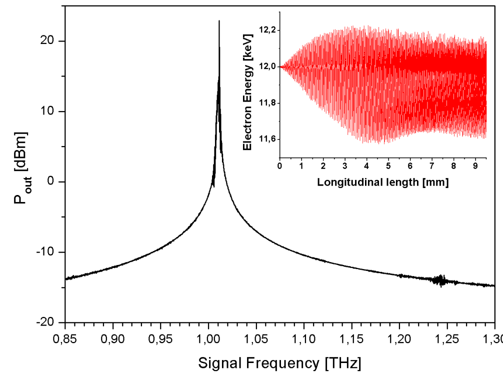

Fig. 5 Output power spectrum and electron energy

The width (Table I) of the sheet electron beam (Fig.4) is chosen by observing in Fig. 3 that, in the region included between 80 m and 160 m, K_p has a maximum 20% reduction with respect to its maximum value. This K_p level assures an effective interaction with the RF field. The distance between the beam axis and the corrugation top is chosen at δ = 15 µm to avoid eventual collisions of the beam with the corrugation and to get the highest allowed level of K_p. The beam current is fixed at 8mA. A uniform focusing magnetic field of 0.9 T is applied to assure a proper beam confinement. To reduce the computational effort in the simulation setup, the cathode was synthesized with an equivalent emitting surface. Copper losses were taken into account. The simulations of the BWO are performed by a 3-D particle-in-cell simulator (Magic3D). Fig.5 shows the output power spectrum. An output power of 190 mW is obtained.

4. Conclusion

An analytical method to compute the dispersion and interaction impedance in backward wave mode for the corrugated waveguide SWS has been used in conjunction with 3-D codes for the design of THz backward wave oscillators. The high output power obtained demonstrates the effectiveness of the method and the feasibility of vacuum devices in THz frequency range.

5. Acknowledgments

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6. References

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