HIGH-POWER SECOND-HARMONIC GYROTRON OSCILLATOR

I. P. Spassovsky, N. A. Nikolov, K. G. Kostov, V. A. Spassov and I. G. Yovchev

University of Sofia, Boul. A. Ivanov 5, Sofia, Bulgaria

Abstract-This paper reports on experimental results from study of nonadiabatic pumped second-harmonic gyrotron oscillator. A steady second-harmonic cavity emission has been observed at 28 GHz and waveguide mode TE_{02}. A peak power of ~ 25MW has been reached with ~ 9percent efficiency. Magnetic field in pumping section regionis modeled and beam pumping is simulated.

I. INTRODUCTION

Cyclotron resonance masers (CRM) are well known as sources of microwave emission in the sentimeter and millimeter regions. The major representatives of CRM are the gyrotrons (1), gyro-travelling wave tube amplifiers (2), the gyroklystrons (3) and the cyclotron autoresonance masers (CARM) (4).

The general resonance condition for CRM is expressed as follows:

$$\omega = k_{\parallel} v_{\parallel} + n\omega_{co}/\gamma \tag{1}$$

Gyrotron operation in the millimeter region meets considerable difficulties connected with high intensity magnetic field generation, because the cyclotron frequency ω_c is proportional to the magnetic field induction B_o , $\omega_c = eB_o/mc\gamma$. The gyrotron mechanism operates also at cyclotron harmonic frequencies. This fact suggests a possibility for reduction of the requisited magnetic field induction by a factor of 1/n. This explain the large interest and the significant achievements in a second-harmonic generation, discussed in a lot of papers (5-7). This paper reports experimental results about the high-power high-current second-harmonic gyrotron oscillator at 28 GHz with electron beam of 550 keV and beam current of ~ 850 A.

II. EXPERIMENTAL SETUP AND RESULTS

Our experimental setup is shown on Fig. 1.

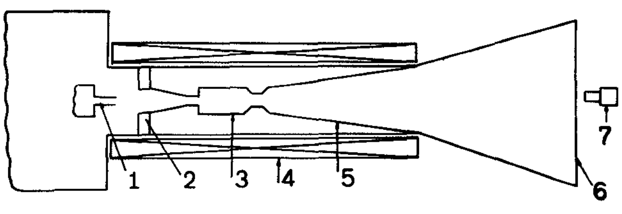

Fig. 1. The full experimental arrangement: 1-graphite cathode, 2-cooper aperture, 3-resonator, 4-solenoidal magnet, 5-conical horn, 6-vacuum window, 7-semiconductor detector.

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A 600 kV Blumlein pulse-line accelerator with a voltage pulse duration of 30 ns is used to generate a hollow electron beam in a foilless diode. Electrons are emitted by a sharp-end cold graphite cathode with a 10 mm diameter through an explosive plasma emission and are propagated in a cylindrical drift tube of a 56 mm diameter.

The beam is created in a pulsing magnetic field from a solenoidal magnet with a space uniformity better than 98 percent. A pulse duration is 4.2 ms and beam is pumped by transit trough a local depression in the external magnetic field.

The external magnetic field B in the aperture region is homogeneous in space but time dependent, $B=B_0 \sin(\omega t)$, where $\omega=2\pi/T$, T=8.4ms. In our modeling the copper aperture is divided into N subapertures thin enough to be treated as a circular loops. The time dependence of electric current into each of them is found as a solution of a system of N first order linear differential equations, with initial conditions $I_j=0$ (j=1,2...N)

$$R_j I_j + \frac{1}{c}\sum_{k=1}^{N} L_{jk}\frac{dI}{dt} = \mathcal{E}_j, \qquad (2)$$

(j=1,2...N)

where: L_{jj} is the induction coefficient for the j-th circular loop, L_{jk} $(j\neq k)$ – the mutual induction coefficient between the j-th and the k-th loop, R_j – the ohmic resistance of the j-th loop, $\mathcal{E}_j$ – the electromotive force created in the j-th loop from the field of the solenoid. The coefficients L_{jk} are calculated according to the well known formulae.

The components of the magnetic field of a single circular loop with a radius b_j are calculated as follows :

$$(B_z)_j = \frac{I_j}{c}\,\frac{2}{\left[(b_j+r)^2+z^2\right]^{1/2}} \times \left[K+\frac{b_j^2-r^2-z^2}{(b_j-r)^2+z^2}E\right] \qquad (3)$$

$$(B_r)_j = \frac{I_j}{c}\,\frac{2(z/r)}{\left[(b_j+r)^2+z^2\right]^{1/2}} \times \left[-K+\frac{b_j^2+r^2+z^2}{(b_j-r)^2+z^2}E\right] \qquad (4)$$

$$(B_\varphi)_j = 0 \qquad (5)$$

where K = K(r,z) and E = E(r,z) are the complete elliptic integrals of the first and second kind. Thus we obtain the components B_r and B_z of the resultant magnetic field from the solenoid and the aperture. The numerical data allow us to construct a z-dependence of B_z and B_r for t=2.1ms, r=const (see Fig. 2).

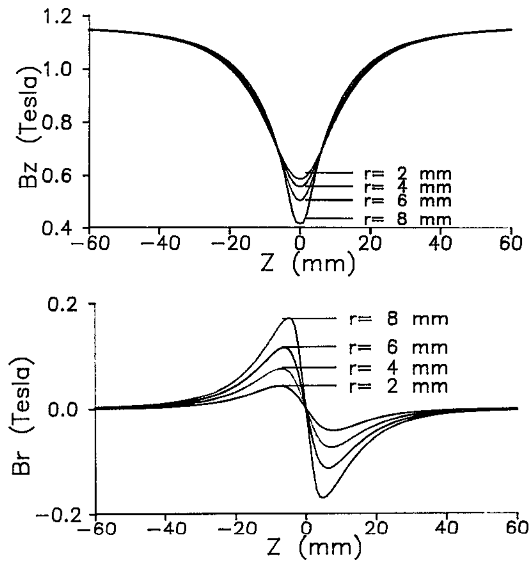

Fig. 2. Calculated B_z and B_r distributions as a function of z coordinate.

To get some information about $v_\perp$ out of the diode, electron propagation from the cathode to the electrodynamical system end has been simulated. For this purpose a computer program has been created to solve in cylindrical coordinates (r, φ, z) the stationary self- consistent problem for propagation of infinitely thin hollow electron beam (with a given initial energy and direction relative to z) from the cathode to the drift tube end. The problem is $2^1/_2$ dimensional ($E_\varphi = B_\varphi = 0$, $v_\varphi \neq 0$). E_φ is the φ - component of the resultant electric field from the beam and electrodynamical system and due to the cylindrical symmetry it is zero. The φ component of the beam magnetic field B_φ is very small compared to the external magnetic field and is neglected. v_φ is the φ component of the electron velocity. In order to found the potential U on a given space grid the Laplas equation $\Delta U = 0$ is solved by the Pieceman - Rackford method which insure a fast convergence,

The beam has been modeled by the movement of one electron in the electric and magnetic fields described by the equation:

$$\ddot{\vec{R}} = (e/mc)\,[\vec{E} + (1/c)(\vec{v} \times \vec{B})], \qquad (6)$$

where R is the electron position. The value of E is calculated as follows:

$$\vec{E} = (\vec{E}_{in} + \vec{E}_{out})/2, \qquad (7)$$

where E_{in} and E_{out} are electrical fields on the inner and outer beam Lager boundaries.

In this simulations a system current increases from zero to some value for which either of the following conditions is fulfilled:

1). $E_z = 0$ on the cathode,

2). $\partial U/\partial y \to \infty$ even in one point of the grid, which is sign of virtual cathode presence.

The longitudinal velocity component $v_\parallel$ from the solution of equation (6) are used for calculation of surface charge density σ of the beam layer at a given current value. The change of E_r along the transition trough the beam layer can be calculated using the value of σ. It has been found that for B_0=10kGs the angle ψ between electron velocity and z is in the range of 42°- 43°, so the pitch ratio $\alpha = v_\perp/v_\parallel = tg\psi \sim 1$. For this value of B the electrons leave the drift tube with energy of 450 keV.

Two cylindrical cavities with equal diameters of 24.8 mm have been fabricated. A map of their cutoff frequencies is shown on Fig. 3.

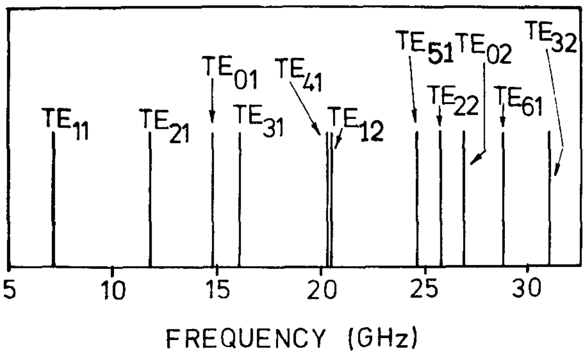

Fig. 3.Map cutoff frequencies of TE_{mn} modes falling between 5 and 32 GHz for the 2.4cm -diameter cavity.

Both cavities have a waveguide narrowing at the cavity entrance with diameter of 12 mm and length L of 15 mm. The waveguide narrowing cutoff frequency is higher than the doubled cutoff frequency of the cavity for the given mode. This fact results in the full reflection from the electrodynamical system entrance with frequency up to ~ $2\omega_c$ for Doppler shifted CRM oscillations and for second-harmonic gyrotron oscillations. One of the cavities terminates by an output conical horn with a slope of 5° and maximum diameter of 56 mm. At the exit of the other cavity there is a cutoff section with 13.5 mm diameter, 12 mm in length and 45° transition towards cavity and the output taper. This cutoff section is supposed to trap gyrotron oscillations at the fundamental cyclotron frequency and to be transparent for second and higher order harmonics of cyclotron frequency as well as oscillations with Doppler shifted frequencies.

A set of experiments has been carried out and aimed to better understand how does the resonators operation depend on the external magnetic field B_0, the local depression ΔB and the space interaction length. When the cavity without a cutoff section at the end has been used a peak output power about 30 MW has been attained. RF frequency is 15 GHz at a waveguide mode TE_{01} and is equal to cyclotron frequency corresponding to B_0 = 10 kGs. So, we draw the conclusion that the cavity operates as a gyrotron at the fundamental cyclotron frequency. The second cavity operation has been studied in more details. A peak power has been attained (25 MW) at a frequency of 28 GHz for operating mode TE_{02}. Fig.4 demonstrates radial-power distribution in horizontal plane for operating mode.

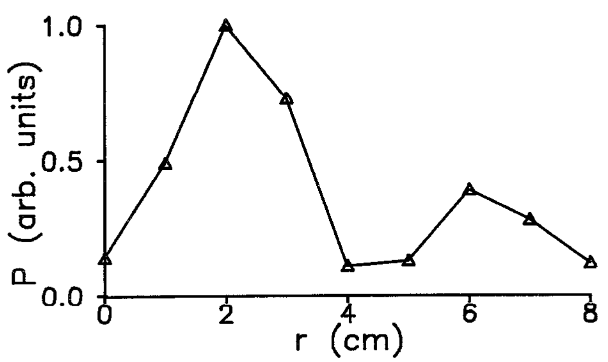

Fig. 4. Radial power distribution for second-harmonic oscillations.

The starting current is about I_s ~ 500 A and the peak power has been reached at I_b ~ 850÷ 950 A with an external magnetic field B_0 = 10 kGs. The measured frequency is twice higher than the fundamental cyclotron frequency for this value of B_0, i. e the gyrotron operate at the second harmonic. ($L_{cav.}$ = 6÷8 cm.). Microwave measurements are performed by special microwave and gas-breakdown technic.

REFRENCES

(1). S. H. Gold et al., "High peak power K - band gyrotron oscillator experiment", Phys. Fluids, vol. 30, pp. 2226-2238, 1987.

(2). K. R. Chu and Antony T. Lin, "Gain and bandwidth of the gyro - TWT and CARM amplifiers", IEEE Trans. Plasma Science, vol PS-16, pp. 90-104, 1988.

(3). K. R. Chu, V. L. Granatstein, P. E. Lathman, W. Lawson and C. D. Strifler, "A 30 - MW gyroklistron amplifier for high - energy linear accelerator", IEEE Trans. Plasma Science, vol. - 13, pp. 424 - 434, 1985.

(4). V. L. Bratman, N. S. Ginsburg, G. S. Nisinovich, M. L. Petelin, "Relativistic gyrotron and cyclotron autoresonance masers", Int. J. Electronics, vol. 51, pp. 541 - 567, 1981.

(5). K. R. Chu, "Theory of electron cyclotron maser interaction in a cavity at the harmonic frequencies", Phys. Fluids, vol. 22, pp. 2354 - 2364, 1978.

(6). B. G. Danly and R. J. Temkin, "Generalized nonlinear harmonic gyrotron theory", Phys. Fluids, vol. 29, pp. 561 - 567, 1986.

(7). D. V. Kissel, G. S. Korablev, V. G. Pavelev, M. I. Petelin, S. E. Cimerman, "Experimental second harmonic gyrotron with optimal RF field", Radiotech. and electronica, vol. 29, pp. 782 - 788, 1978.