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Research Article

Application of a Single Lens in a Direct Floating Klystron

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ABSTRACT
In this paper we consider the possibility of using an integrated single lens in the region of the concentration of the electric field of the resonator to modulate the electron flux in terms of velocity. It is shown that the use of the single lens as a velocity modulator does not affect the magnitude of the interaction coefficient of the electron beam with the field of the lens.In addition, the possibility of using a single lens to focus the electron beam in ultrahigh frequency devices with vertical direction klystron type has been demonstrated. This issue is considered by solving a differential equation for the trajectory of particles moving in electrostatic field with rotational symmetry in the first approximation.

Index terms: Microwave electronics, modulation, single lens, electron beam, differential equation.

INTRODUCTION
In microwave electronics for calculating and creating powerful amplifiers and generators, great attention is paid to the formation of a powerful electron beam of various configurations and its transportation over considerable distances. The theory of the formation of electron beams of high intensity is devoted to a number of theoretical studies [1-3]. There are known methods of transporting electron fluxes in microwave devices with a klystron mechanism of interaction between the input and output resonators by means of various static electric and magnetic fields [4]. The necessity of applying these fields is due to the influence of space charges and Coulomb forces of repulsion of the space charge on the trajectory of the electron motion. Generally, focusing actions of electric and magnetic fields are carried out in the drift space of microwave devices.

1. Velocity modulation of electron beams
Consider a three-electrode single lens whose electrodes consist of three flat coaxial diaphragms arranged at equal distance *s* from each other, parallel to each other (Fig. 1).

The axial distribution of the electrostatic potential $\Phi(z)$ is represented in the form [5,6].

$$\Phi(z) = \Phi_0 \left(1 - \frac{\chi^2}{1 + \left(\frac{z-s}{d} \right)^2} \right) \quad (1)$$

where $\Phi_0 -$ the potential of free space, $\chi^2 -$ parameter that varies within $0 < \chi^2 < 1$, $d -$ the diameter of the apertures of the diaphragms. The origin is compatible with the plane of the middle electrode, and the *z*-axis is the symmetry axis of the system. Let the alternating voltage be applied to the outer electrodes of a single lens with a frequency ω and amplitude U_m

$$U = U_m \sin \omega t \quad (2)$$

t_0 is the passage period of some electron through the center of the middle electrode of the lens. Then, neglecting the small change in the electron velocity inside the lens it can be writes as:

$$t = t_0 + \frac{z}{\vartheta_0}. \quad (3)$$

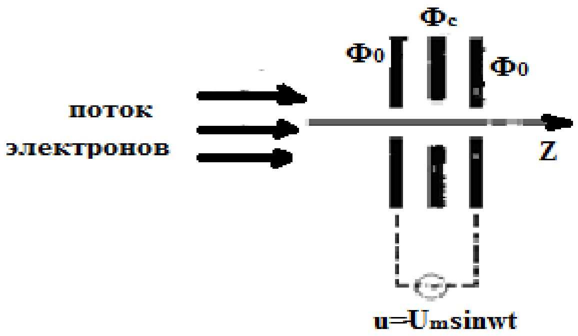

Figure 1. The alternating voltage is applied to the extreme electrodes of single lens

The total kinetic energy of an electron entering the lens with an initial velocity

$$\vartheta_0 = \sqrt{\frac{2e\Phi_0}{m}}, \quad (4)$$

magnitude on the output of the lens

$$W = e\Phi_0 + \Delta W, \quad (5)$$

where the increment of the kinetic energy can be represented in the following form:

$$\Delta W = \frac{eU_m}{2s}\left[\int_{-s}^{s} \sin\left(\omega t_0 + \frac{\omega z}{\vartheta_0}\right)dz + \frac{2s}{\Phi_0}\int_{-s}^{s} \Phi'(z)\sin\left(\omega t_0 - \frac{\omega z}{\vartheta_0}\right)dz\right]. \quad (6)$$

Dashes represent the differentiation of *z* coordinate. After integration, the increment of the kinetic energy can be written as:

$$\Delta W = eU_m\left[M - \frac{\omega}{\vartheta_0}\chi^2 I_1(z)\right]\sin \omega t_0 + \chi^2\left[-\sin\frac{\theta}{2} + \frac{\omega}{\vartheta_0}\chi^2 I_2(z)\right]\cos \omega t_0. \quad (7)$$

the following notation is introduced as:

$$I_1(z) = \int_{-s}^{s} f(z)\sin\frac{\omega z}{\vartheta_0}dz, \quad (8)$$

$$I_2(z) = \int_{-s}^{s} f(z)\cos\frac{\omega z}{\vartheta_0}dz, \quad (9)$$

$$f(z) = \left[1 + \left(\frac{z}{d}\right)^2\right]^{-1}. \quad (10)$$

The value of $\theta = \frac{2\omega s}{\vartheta_0}$ characterizes the undisturbed angle of electrons beams through the lens, and *M* represents the interaction coefficient between electron beam and field of a single lens

$$M = \frac{\sin \theta/2}{\theta/2} \quad (11)$$

The calculations show that the integral $I_1(z)$ goes to zero. Thus, the use of a single lens as a velocity modulator does not affect the magnitude of the interaction coefficient of the electron beam with the field of the lens. Due to smallness of undisturbed angle of flight, under condition

$$s = \int_{-s}^{s} f(z) \cos \frac{\omega z}{\vartheta_0} dz, \quad (12)$$

conservation of sinusoidal law of the change in the increment of the kinetic energy occurs

$$\Delta W = eMU_m \sin \omega t_0. \quad (13)$$

Then, taking into account the smallness of the amplitude of the alternating voltage in comparison with the potential at the outer electrodes of a single lens, the electron velocity ϑ on the output lens can be written as:

$$\vartheta \approx \vartheta_0 \left(1 + \frac{MU_m}{2\Phi_0} \sin \omega t_0 \right). \quad (14)$$

Thus, the use of a single lens as a velocity modulator of the electron beam practically does not change the magnitude of the interaction coefficient of the electron beam with the field of the lens, but the presence of an average electrode makes it possible to focus the electron beam in the vertical direction.

2. Advantages of proposed input resonator circuit

In the cavity resonators of the classical scheme, the concentrated capacitance is formed by a flat gap in the form of plane-parallel grids in the center of the resonator and concentrated inductance as toroidal surface.In microwave devices with a klystron interaction mechanism, cavity resonators are used as input and output devices.The input resonator capacitance has high positive potential and primarily concentrated with high-frequency electric field. During the high-frequency field, the electron beam is modulated by velocity and transferred to density modulation in the drift space of the microwave device. Then, in the output resonator, the energy of the modulated electron beam is removed as it enters the output resonator in the decelerating mode of the electric field. The disadvantage of the input cavity resonators described above is: firstly, the presence of grids, which are mechanical obstacles in the path of the electron beam; secondly, the saggy equipotential surfaces near the grids that exert scattering effect on the electrons. These factors reduce the value of the convection current, that reduces the power of the microwave devices. Therefore, in conventional circuits of such microwave devices, it becomes necessary to use various transport systems in drift space: a system of a homogeneous or inhomogeneous magnetic field, a system of a homogeneous or inhomogeneous electric field.A positive result can be achieved by replacing capacitor consisting with two parallel grids where high-frequency electric field occurs, by a single lens with three diaphragms.

Figure 2 shows the design of the proposed device [8]. This device is a toroidal resonator (1) in which a single lens consisting of three diaphragms with round holes of equal diameters are installed in the region of the concentration of the high-frequency electric field, at which the extreme electrodes (2) are at the same high accelerating potential where high-frequency electric field is applied.The middle diaphragm (3) is installed with thin conducting threads (4), passed through the slits (5), parallel to the current lines located on opposite surfaces of the toroid, a potential different from the accelerating potential is applied to the diaphragms on the edge. The set of three diaphragms make a single lens. The focal length is regulated by the potential of the middle diaphragm Φ_c.

The outer electrodes of a single lens are at a potential Φ_0 equal to the potential of the space surrounding the lens, and the potential Φ_c on the internal electrode may be greater or less than the potential of the outer electrodes.A single lens in all cases will be a collecting lens [7].We assume that $\Phi_c > \Phi_0$. Such resonator has the possibility of vertical focusing of the electron beam in microwave devices with a klystron interaction mechanism [6, 8, 9].

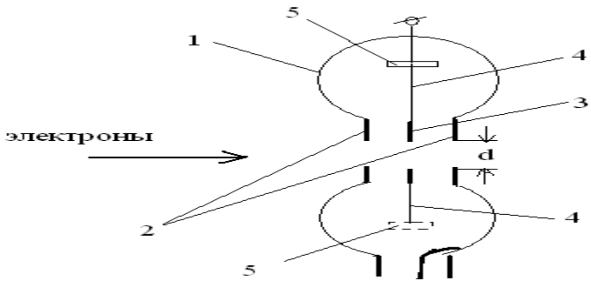

Figure 2 -Toroidal resonator with electrostatic focusing

3. Focusing of electrons in the vertical direction

Let an intense flux of electrons, possessing axial symmetry with respect to the z-axis of the cylindrical coordinate system, fall on a single lens.The electrostatic potential satisfies the Poisson equation:

$$\Delta\varphi(r,z) = -\frac{1}{\varepsilon_0}\rho(r,z) \qquad (15)$$

We seek the potential and bulk charge density $\rho(r,z)$ in the form of power series:

$$\varphi(r,z) = \sum_{n=0}^{\infty} a_{2n}(z) r^{2n}, \qquad (16)$$

$$\rho(r,z) = \sum_{n=0}^{\infty} b_{2n}(z) r^{2n} \qquad (17)$$

Substitution of expressions (16), (17) into equation (15) allows us to determine the coefficients $a_{2n}(z)$ by means of the recurrence relation:

$$a_{2n+2}(z) = -\frac{a''_{2n}(z) + \frac{1}{\varepsilon_0} b_{2n}(z)}{(2n+2)^2}. \qquad (18)$$

The electrostatic potential $\varphi(r,z)$ with respect to the quantities of the second order of smallness can be represented in the following form:

$$\varphi(r,z) = \Phi(z) - \frac{1}{4}\left[\Phi''(z) + \frac{1}{\varepsilon_0}\rho(z)\right] r^2 + \ldots, \qquad (19)$$

where the notation is introduced as

$$a_0(z) \equiv \Phi(z); b_0(z) \equiv \rho(z). \qquad (20)$$

The repulsion force of the space charge can be taken into account from the Gauss theorem:

$$\frac{\partial\varphi}{\partial r} = -\frac{\rho(z)}{2\varepsilon_0} r. \qquad (21)$$

Then the equation of the electrons path considering the space charge and Coulomb repulsion forces can be written as follows:

$$2\Phi(z)r'' + \Phi'(z)r' + \frac{1}{2}\left[\Phi''(z) + \frac{2}{\varepsilon_0}\rho(z)\right]r = 0 \quad (22)$$

To represent the vertical direction focus in the paraxial approximation, it is necessary to satisfy the following condition:

$$\frac{2}{\varepsilon_0}\rho(z) \ll \Phi''(z) \quad (23)$$

If this condition is satisfied, the differential equation (22) can be solved by the method of successive approximation. We can rewrite equation (22) in the form:

$$2\Phi(z)r'' + \Phi'(z)r' + \frac{1}{2}\Phi''(z)r = -\frac{1}{\varepsilon_0}\rho(z)r \quad (24)$$

The general solution of the inhomogeneous differential equation can be represented as follows

$$r(z) = R(z) + \Delta r(z) \quad (25)$$

Where

$$R(z) = ag(z) + bh(z) \quad (26)$$

is a general solution of the corresponding homogeneous equation, *a* and *b* are arbitrary constants, g(z) and h(z) are linearly independent particular solutions of the homogeneous equation, and $\Delta r(z)$ is a particular solution of the inhomogeneous equation.

The general solution of the inhomogeneous equation with initial conditions, also taking into account the parallel motion of the electrons in front of the input device, takes the form:

$$\Delta r = l\{a[g(z)J_1 - h(z)J_2] + b[g(z)J_3 - h(z)J_1]\}, \quad (27)$$

and

$$r(z) = r_0\left[g(z)\left(1 - \frac{I_1}{2\varepsilon_0\sqrt{\Phi_0}}\right) + \frac{I_2}{2\varepsilon_0\sqrt{\Phi_0}}h(z)\right]. \quad (28)$$

where

$$J_1(z) = \int_{z_0}^{z} \frac{g(z)h(z)\rho(z)}{\sqrt{\Phi(z)}}dz, \quad (29)$$

$$J_2(z) = \int_{z_0}^{z} \frac{g^2(z)\rho(z)}{\sqrt{\Phi(z)}}dz, \quad (30)$$

$$J_3(z) = \int_{z_0}^{z} \frac{h^2(z)\rho(z)}{\sqrt{\Phi(z)}}dz, \quad (31)$$

$$l = \frac{1}{2\varepsilon_0\sqrt{\Phi(z)}[g'(z)h(z) - g(z)h'(z)]}. \quad (32)$$

l - is a constant magnitude, proportional to the differential Lagrange invariant, Δr - characterizes the error of the first-order image in an arbitrary plane.

Let the initial conditions for the particular solutions g(z), h(z) of the homogeneous equation be satisfied:

$$g(0) = 1;\ g'(0) = 0;\ h(0) = 0;\ h'(0) = 1. \quad (33)$$

which is followed by

$$a = r_0;\quad b = r_0'. \quad (34)$$

r_0 - characterizes the coordinate of the initial point, r_0' - is the initial slope of the particle trajectory to the z-axis. Where l will take the following value:

$$l = -\frac{1}{2\varepsilon_0\sqrt{\Phi_0}} . \qquad (35)$$

Taking into account (33), (34), and (35), expression (28) takes the form::

$$r(z) = r_0[g(z) - \frac{1}{2\varepsilon_0\sqrt{\Phi_0}}(g(z)J_1 - g(z)J_2] + r_0^1[h(z) - \frac{1}{2\varepsilon_0\sqrt{\Phi_0}}(g(z)J_3 - h(z)J_1)] . \qquad (36)$$

For the electrons moving parallel to the z axis in front of the input device, the slopes of the trajectory are zero r_0'. Simplified equation (36) can be written as:

$$r(z) = r_0[g(z)\left(1 - \frac{1}{2\varepsilon_0\sqrt{\Phi_0}}J_1\right) + \frac{1}{2\varepsilon_0\sqrt{\Phi_0}}h(z)J_2] . \qquad (37)$$

The thin single lens approximation for the image space satisfies the relation

$$(r')_2 = -\frac{r_0}{8\sqrt{\Phi_0}}\int_{-\infty}^{\infty}\frac{\Phi'(z)}{\Phi^{3/2}(z)}dz \qquad (36)$$

Where the focal length of a single lens can be derived as

$$f_2 = -\frac{r_0}{(r')_2} = -\frac{1}{g_2'} . \qquad (37)$$

On the other side, the focal length of the lens should be equal to the drift space length L of the of the klystron type microwave device

$$L = -\frac{1}{g_2^1} . \qquad (38)$$

Index "0" refers to the corresponding values in the object space.

4. CONCLUSION

Proposed design of the toroidal resonator can simultaneously perform the role of the electron velocity modulator and the transport system in the drift space where electron bunches can be focused on the surface of the entrance window of the output resonator. Such a resonator with electrostatic focusing enhances the power of klystron type microwave devices by increasing the convection current.

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10. Annotations: In this paper work we consider the possibility of using a single lens to modulate the electron beam velocity. It is shown that the use of a single lens as a modulator in speed does not affect the value of the coefficient of interaction with the electron flux field lens.

11. Keywords: electronics UHF, modulation, lens, electron beam.

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