MULTIMIRROR QUASI-CYLINDRICAL CAVITY RESONATORS FOR FREQUENCY-TUNABLE GYROTRONS

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UDC 537.86

We consider the possibility to create a gyrotron with smooth mechanical frequency tuning on the basis of multimirror quasi-optical resonators. The two-dimensional problem of finding eigenmodes at the open quasi-cylindrical resonator of such a type is solved. Parameters of the gyrotron based on such a device, namely, its efficiency and starting current, are estimated.

1. INTRODUCTION

Many applications, such as spectroscopy, diagnostics and monitoring of various media, dynamic polarization of nuclei, etc., require submillimeter-wave electromagnetic radiation sources which enable smooth frequency tuning [1, 2]. Promising devices of this type are gyrotrons having comparatively low power levels compared with the controlled-fusion gyrotrons, specifically, in the range from 10 to 1000 W.

In a gyrotron with a cavity in the form of a section of the circular waveguide, the possibility to tune the frequency $f$ of the output radiation is limited by the narrow resonance band $\Delta f$ equal to several thousandths of $f$, namely, $\Delta f/f \sim 1/Q$, where the typical Q-factor $Q$ of the gyrotron cavity amounts to about $10^3$. Smooth tuning of the output-radiation frequency in a wider range can be achieved by varying the cavity geometry mechanically. For example, in a coaxial gyrotron, this can be done by using longitudinal displacements of an inner coaxial conductor of variable radius [3, 4].

In this paper, we consider a gyrotron with a multimirror cavity resonator which allows one to tune the radiation frequency by changing relative positions of the mirrors. However, the azimuthal nonuniformity of the working mode reduces the efficiency and increases the starting current. Because of this fact, two-mirror gyrotrons have not been used in controlled-fusion devices. However, a multimirror, specifically, a five-mirror system ensures acceptable uniformity of the field. Moreover, for spectroscopic problems, the efficiency and the starting current are not so important as they are for high-power gyrotrons used in controlled-fusion devices.

The radiation can be output from a multi-mirror gyrotron both in the classical way and through one of the mirrors due to its translucency (Fig. 1). In this case, a cutoff narrowing is arranged for the working mode at the cavity ends to reduce the diffraction loss of this mode. The radiation of the working mode to

Fig. 1. Ray structure of the mode of a five-mirror gyrotron in its cross section. The arrow shows the direction of the radiation output.

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the cavity slot can be reduced by means of a weak deformation of its boundary [5]. In this paper, these problems are solved within the two-dimensional approximation for the TE modes used in gyrotrons.

2. FIELD IN A WEAKLY DEFORMED CYLINDRICAL CAVITY RESONATOR

Fig. 2. Approximate boundary conditions on the unperturbed surface. Here, \( l \) is the distance between the perturbed and unperturbed boundaries, so that \( l > 0 \) for the narrowing of the cavity and \( l < 0 \), for its widening, \( \mathbf{n} \) is the inward normal to the metal surface, and \( \tau \) is the unit vector tangential to the unperturbed surface.

If the boundary deformation is small compared with the wavelength \( \lambda \) such that \( l \ll \lambda/2 \), then one can specify the equivalent boundary conditions on the unperturbed circular boundary for the transverse problem (Fig. 2) [6]:

\[
(E, \tau) = ik (\mathbf{ln}, \mathbf{H}, \tau) + (\tau \nabla) (E, \mathbf{ln}),
\]

(1)

where \( k = 2\pi/\lambda \) is the wave number, and \( E \) and \( H \) are the electric and magnetic fields, respectively. In the polar coordinates \( r \) and \( \phi \), the equation of the surface can be represented as \( r = r_w + \delta(\phi) \), where \( \delta = -l \) and \( r_w \) is the radius of the unperturbed surface, i.e., the round cylinder. The TE modes can be described by using the magnetic Hertz potential \( \Pi \). In this case, the magnetic Hertz vector \( \Pi^m = \Pi e_z \). Equivalent boundary condition (1) written for the magnetic Hertz potential \( \Pi \), takes the form

\[
\frac{\partial \Pi}{\partial \mathbf{n}} + g^2 \delta(\phi) \Pi - \frac{1}{r_w^2} \frac{\partial}{\partial \phi} \left( \delta(\phi) \frac{\partial \Pi}{\partial \phi} \right) = 0,
\]

(2)

where \( g \) is the transverse wave number.

Any perturbation of the shape of the cavity wall can be expanded into a Fourier series \( \delta(\phi) = \sum_m a_m \exp(\imath m\phi) \), where \( a_m = a_{-m}^* \), and the field can be represented in the form of the series \( \Pi = \sum_m \Pi_m = \sum_m C_m J_m(\text{gr}) \exp(\imath m\phi) \), where \( J_m \) is a Bessel function of order \( m \). Substituting this expansion into boundary condition (2), we obtain implicit expression for the coefficients \( C_m \):

\[
C_m = -\frac{g \sum_n \left( 1 + \frac{m^2 - mn}{\nu_w^2} \right) a_n C_{m-n} J_{m-n}(\nu_w)}{J'_m(\nu_w)} , \quad \nu_w = g r_w .
\]

(3)

Expression (3) contains a resonance denominator that vanishes in the case of partial modes of the unperturbed system. If the ray structure of the mode \( \Pi_m \) occupies approximately the same position after \( N \) reflections, where \( N \) is a relatively small integer number, then the partial frequencies of the modes \( \Pi_m \), \( \Pi_{m-N} \), and \( \Pi_{m+N} \) will be close to each other [7], which ensures their strong coupling in system (3). In accordance with the Debye asymptotics, the roots of the equation \( J'_m(\nu_q) = 0 \), where \( J'_m \) is the derivative of the Bessel function with respect to its argument are determined by the following relation for large values of the radial and azimuthal indices \( q \gg 1 \) and \( m \gg 1 \):

\[
\nu_q \sin \psi = m\psi + \pi (q - 3/4).
\]

(4)

Here, the angle \( \psi \) is determined from the relationship \( \sin \psi = \sqrt{1 - m^2/\nu_q^2} = \sqrt{1 - r_c^2/r_w^2} \) and is equal to one half of the angle between two successive reflections of the ray within the geometric-optical representation of the mode, where \( r_c \) is the caustic radius. The ray structure will be closed under the condition \( \psi = \pi n/N \), where \( n = 1, \ldots, [N/2] \), and \( [N/2] \) is the integer part of \( N/2 \). For \( n = [N/2] = s \) and odd \( N \), the structure of the mode is an \( N \)-pointed star. Equation (4) relates the radial and azimuthal indices of the mode. If