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Electrodynamic Properties of Coupled Quasi-Optical Open Cavities in Sources of Millimeter Radiation

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Abstract—The results of experimental studies of electrodynamic properties of coupled open millimeter-range cavities are presented. Cavities of the considered type can be employed in such electron devices as an orotron and an oscillator of diffraction radiation. It is demonstrated that a system of two open cavities coupled through strip diffraction gratings is best suited for the broadening of the transmission band of an open cavity system, allowing, at the same time, the Q factor to be sustained at a high level. The transmission band of such a system is five times broader than the transmission band of open cavities placed in series with respect to a distributed source emitting volume waves. Practical schemes of electron devices using coupled open cavities are described and analyzed. The results of experimental studies of some of these devices in the millimeter wavelength range are presented.

1. INTRODUCTION

An orotron and a diffraction radiation oscillator (DRO), which employ in their operation the Smith–Parsell coherent effect (diffraction radiation) [1, 2], are now adequately understood theoretically and thoroughly investigated experimentally [3–5]. One of the ways of further development of such devices is associated with the improvement of the electrodynamic system of these devices aimed at expanding their functional capabilities and increasing the efficiency of converting the energy of an electron flux into radiation energy. Diffraction electronic devices based on coupled open cavities, which were proposed and partially analyzed in [5–9], possess several important advantages over single-cavity DROs. Such devices have a broader range of electron frequency tuning and can be employed as efficient power amplifiers and frequency multipliers. Open cavities may be coupled in such devices either through the field undergoing diffraction on mirror edges in the case when cavities are placed in series along the axis of the electron flux [8, 9] or through the field undergoing diffraction on strip gratings in the case when open cavities are placed in parallel with respect to the axis of the electron flux [6, 7]. The first scheme of coupling of open cavities has been studied in [10, 11] in the case of open cavities with short-focal-length mirrors whose curvature radius and aperture sizes are much less than the curvature radius and aperture sizes of conventional quasi-optical cavities. The practical implementation of such devices is hampered by the absence of an adequate data on the electrodynamic properties of resonant systems of these devices.

In this paper, we experimentally model the current wave of spatial charge in the electron flux as a surface wave of a dielectric waveguide and investigate spectral and resonant characteristics of coupled open cavities in the millimeter range. Our studies reveal the possibility of considerable broadening of the transmission band of coupled open cavities with respect to the transmission band of a single cavity. Practical schemes allowing the implementation of orotron and DRO devices based on coupled cavities are discussed. A high potential of such devices is confirmed by the results of experimental studies performed with some modifications of DROs.

2. PROCEDURE AND OBJECTS OF STUDIES

As demonstrated in [4, 5], the method of experimental modeling when radiation of a current wave in spatial charge of the electron flux is modeled as radiation of a surface wave of a planar dielectric waveguide located near a diffraction grating is an efficient method for the solution of problems of diffraction electronics. The Q factor of two coupled cavities without an electron flux within the framework of this approach can be estimated with the use of the following relationship [12]:

$$Q_S = \frac{W_1 + W_2}{P_1 + P_2}\bar{\omega}_R, \tag{1}$$

where W_1 and W_2 are the energies stored in the first and second cavities, respectively; P_1 and P_2 are the powers of losses in the cavities; and $\bar{\omega}_R$ is the resonance frequency.

Introducing the Q factors of separate cavities Q_1 and Q_2, we can apply formula (1) to derive the following inequalities:

$$Q_1 \ge Q_S \ge Q_2 \quad \text{for} \quad Q_1 \ge Q_2, \tag{2}$$

$$Q_2 \ge Q_S \ge Q_1 \quad \text{for} \quad Q_2 \ge Q_1. \tag{3}$$

Inequalities (2) and (3) indicate that the Q factor of a system of coupled cavities may exceed the Q factor of one of the cavities due to energy redistribution in the interaction of the fields in open cavities. In the case of identical cavities ($Q_1 = Q_2$), the total Q factor of the system is no lower than the Q factors of separate cavities. This analysis reveals the possibility of broadening the transmission band of a system of coupled open cavities and keeping high values of the Q factor.

Figure 1 presents diagrams of electrodynamic systems of coupled open cavities under investigation. A system where open cavities are placed in series with respect to the axis of a dielectric waveguide and are coupled through the field undergoing diffraction on the mirrors is shown in Fig. 1a, while a system where open cavities are placed in parallel with respect to the axis of a dielectric waveguide and are coupled through diffraction gratings is presented in Fig. 1b.

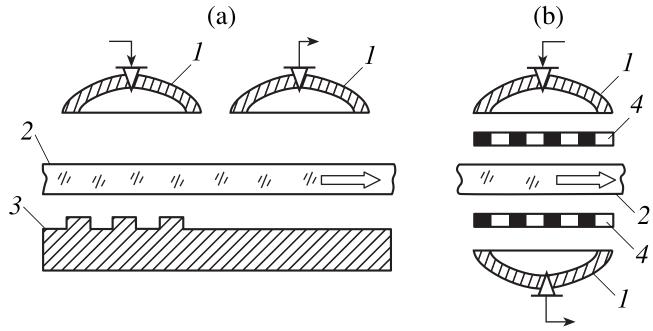

Fig. 1. The studied electrodynamic systems based on coupled open cavities: (*1*) mirrors of open cavities allowing radiation energy to be coupled out of the cavity, (*2*) dielectric waveguide, (*3*) mirror with a reflective diffraction grating, and (*4*) mirrors with strip diffraction gratings.

Systems of coupled open cavities consist of spherical mirrors *1* with curvature radii $R = 60$ mm and apertures $A = 55$ mm reduced down to 35 mm along the axis of the dielectric waveguide *2*. The lower plane mirror *3* in the system shown in Fig. 1a had either a reflective or strip diffraction grating and served as a common mirror for the first and second open cavities. In the system with parallel open cavities, plane mirrors *4* with strip diffraction gratings in their central sections were placed between spherical mirrors.

Parameters of the gratings were calculated in such a way as to ensure the central frequency $f_0 = 46$ GHz. These gratings transformed a surface wave of the dielectric waveguide into a volume wave propagating in the open cavity along the normal to the surface [4]. The energy was coupled out of the systems under study through coupling slits in the spherical mirrors. Next, the signals were transformed on detectors and were entered into registration devices. The dielectric waveguide was included into a standard measuring scheme, which is often employed to perform measurements of this kind [4, 5].

To determine the specific features of the above-described multiply coupled electrodynamic systems, we investigated the spectra of resonance frequencies and resonance characteristics of oscillations in coupled open cavities. Equivalent characteristics measured for single hemispherical and spheroidal open cavities were employed as reference data.

3. SPECTRAL AND RESONANCE CHARACTERISTICS OF COUPLED OPEN CAVITIES

Figure 2 displays the spectra of resonance frequencies corresponding to a variation in the distance between the mirrors (H) in the system where the cavities are coupled through the diffraction field (Fig. 1a) and in a reference hemispherical open cavity. The spectra presented in Fig. 2 characterize the capability of the considered resonance system to support a limited number of TEM_{mnq} oscillation modes [4], where the indices $m, n = 0, 1, 2, \ldots$ correspond to the transverse components of oscillations and q is the longitudinal index determining the number of half-waves stacked along the axis of the open cavity.

Figure 2a shows that, as the distance between the mirrors changes, oscillations corresponding to the fundamental TEM_{00q} mode exist in a hemispherical open cavity within the entire frequency range $f = 45$–47 GHz. The insertion of a dispersive element in the form of a reflective diffraction grating into an open cavity lifts the degeneracy of the resonant system in the transverse indices m and n. The TEM_{20q} oscillation mode is usually defined as a fundamental mode for such a system [5]. In addition, depending on the parameters of the open cavity and the diffraction grating, other types of higher order oscillations (e.g., TEM_{02q}) having a considerable influence on the mechanism of coupling of two open cavities through diffraction fields may be excited in the system under consideration. Therefore, in the first scheme of coupled open cavities (Fig. 1a), the reflective diffraction grating placed in one of the cavities served as an excitation element for the entire system. The spectra of resonance frequencies and characteristics of vibrations were investigated through the hemispherical open cavity without the diffraction grating, which allowed us to compare the properties of single and coupled open cavities under conditions when the influence of higher order oscillation modes is reduced to a minimum.

Figure 2b displays the spectra of resonance frequencies of two coupled open cavities in the case when the cavity with a diffraction grating is tuned to the frequency $f = 46$ GHz ($H_1 = 33$ mm). As can be seen from these spectra, the hemispherical open cavity without a diffraction grating is excited at the edge points of the frequency range within the interval $H_2 = 27$–33 mm. Oscillations do not arise around the resonance frequency of the open cavity with the diffraction grating,

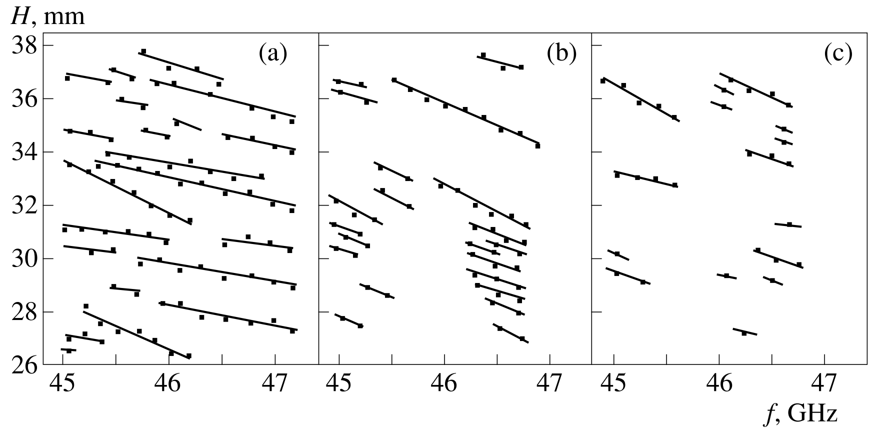

Fig. 2. Spectra of resonance frequencies of (a) a hemispherical open cavity and (b, c) diffraction-coupled open cavities with (b) reflective and (c) strip diffraction gratings.

which is due to the minimum amplitude of the diffraction field in the case when the diffraction grating–dielectric waveguide system emits radiation along the normal. When the detuning from the frequency f_0 varies within the interval $\Delta f \approx \pm 1$ GHz, the angle of the radiation pattern deviates from the normal, which increases the intensity of the diffraction field and leads to the excitation of the second cavity around the edges of the frequency range. As the distance H increases, the coupling between the cavities becomes stronger, reaching its maximum magnitude when the distances between the mirrors are equal to each other ($H_1 = H_2$). In this case, oscillations in the second open cavity arise even around the frequency $f \approx 46$ GHz.

Coupled open cavities with a strip grating at the center of the common plane mirror (Fig. 1a) possess similar properties. The decrease in the number of oscillation modes in such a system (Fig. 2c) is due to the selective properties of the employed diffraction grating [5]: the intensity of radiation emitted from the volume of the open cavity to free space through the diffraction grating reaches its maximum with $H \approx (\lambda/4)(2N + 1)$, while the accumulation of energy inside the volume of the open cavity is characteristic of the values $H \approx (\lambda N)/2$, where λ is the radiation wavelength, $N = 1, 2, \ldots$. The magnitude of field coupling in open cavities reaches its maximum when the distances between the cavities are approximately equal to each other, i.e., when the cavities are tuned to close frequencies. Typical resonance characteristics of oscillations of the above-described coupled open cavities are presented in Fig. 3, where P/P_{max} are the values of the oscillation power in open cavities normalized to the maximum power P_{max}. The resonance curve of a single hemispherical open cavity is shown for comparison by curve *1* in the same figure. As can be seen from the presented plots, the transmission band of coupled open cavities measured at the level of $0.5P_{max}$ increases by a factor of nearly two, reaching the value $\Delta f \approx 250$ MHz. The resonance curves corresponding to coupled open cavities with reflective and strip diffraction gratings virtually coincide with each other under these conditions, which indicates the existence of efficient coupling in these systems through the diffraction of the fields at the periphery of the mirrors.

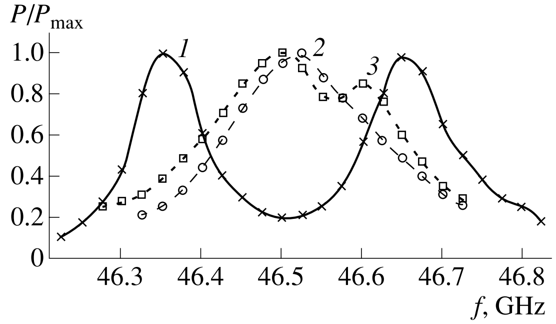

Fig. 3. Resonance curves of (*1*) a hemispherical open cavity and (*2*, *3*) coupled open cavities with (*2*) strip and (*3*) reflective diffraction gratings.

Figure 4a displays the spectra of resonance frequencies of a spheroidal open cavity, which is a basis element for the second scheme of coupled cavities (Fig. 1b). Similar to the case of a hemispheric open cavity, the TEM_{00q} mode is the fundamental oscillation mode in this case. The structure of the field in a spheroidal open cavity is the same as in a hemispherical open cavity [4]. However, the frequency separation between the oscillations in a spheroidal open cavity is two times less than in a hemispherical open cavity (Fig. 2a). When additional plane mirrors with strip diffraction gratings in their central parts are inserted into a spheroidal open cavity, the oscillation spectrum of the coupled system (Fig. 4b) qualitatively correlates with the oscillation spectrum of a hemispherical open cavity (Fig. 2a). Strip diffraction gratings couple two hemispherical open cavities simultaneously filtering the angular spectrum of plane waves excited in the system

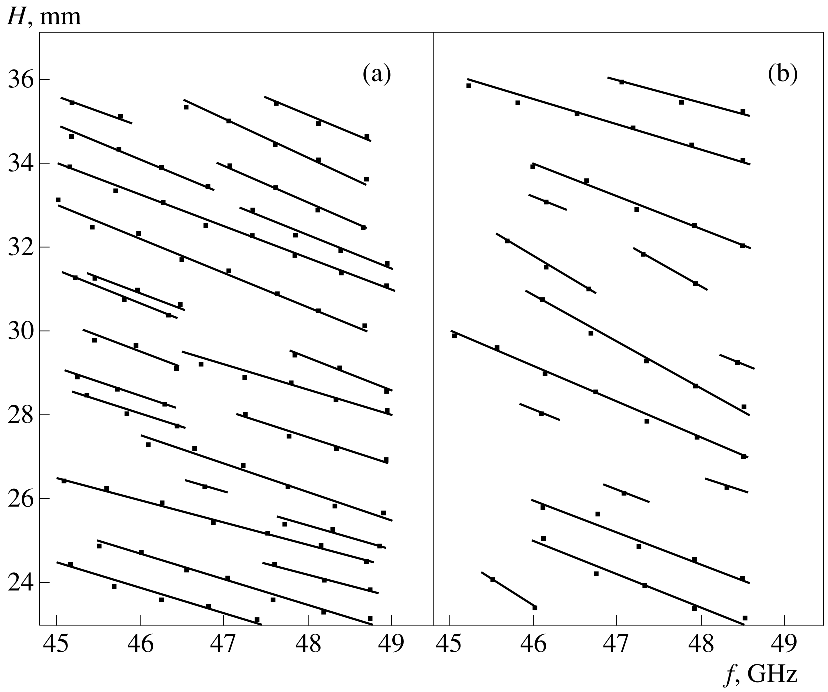

Fig. 4. Spectra of resonance frequencies of (a) a spheroidal open cavity and (b) a system of cavities coupled through diffraction gratings.

under study. Consequently, variations in the positions of these diffraction gratings in the resonant volume relative to the spherical mirrors change the spatial distribution of the fields corresponding to the oscillation modes excited in the considered system of coupled open cavities. Similar to a hemispherical open cavity with a reflective diffraction grating, TEM_{20q} and TEM_{02q} oscillation modes, as well as higher order oscillation modes arising due to the insertion of a coupling element in the form of a double strip diffraction grating, may exist in the system under study. A small change in the slope of mechanical frequency tuning of coupled open cavities (Fig. 4b) with respect to the slope of the tuning curve characteristic of a spheroidal open cavity (Fig. 4a) indicates the conservation of the Q factor of the system under investigation.

Measurements of the resonance curves for coupled open cavities have demonstrated that, when the open cavities are tuned to close frequencies, the transmission band of the system becomes much broader than in the case when the cavities are coupled through the fields undergoing diffraction on mirrors. Specifically, Fig. 5 presents the resonance curves for open cavities coupled through strip diffraction gratings and for a spheroidal open cavity. The maximum transmission bandwidth of the coupled system was fixed within the range $f = 45–47$ GHz for equal distances of spherical mirrors from the planes of the coupling element with a total distance between the spherical mirrors equal to $H = 31$ mm. The transmission bandwidth measured at the $0.5P_{max}$ power level was equal to $\Delta f \approx 1.3$ GHz. The narrowing of the transmission band of coupled open cavities observed in the case of blue detunings ($f = 48.5$ GHz) is due to the deviation of the radiation pattern of the diffraction grating–dielectric waveguide system from the normal and, correspondingly, the decrease in the coefficient of coupling between the cavities.

Comparing the values of Δf for the basis components and coupled systems, we find that, the maximum transmission bandwidth in resonance systems with comparable H can be achieved when two open cavities are coupled through strip diffraction gratings: the transmission band of a system where open cavities are placed in parallel is almost five times broader than the

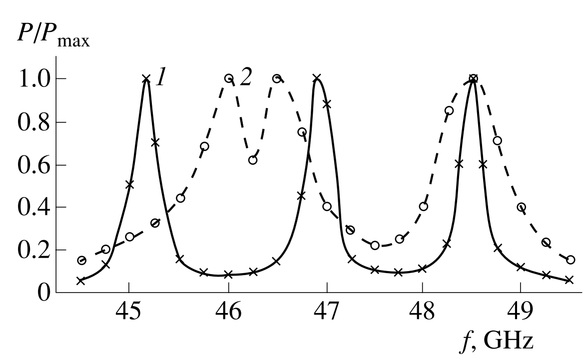

Fig. 5. Resonance curves of (*1*) a spheroidal open cavity and (*2*) a system of cavities coupled through diffraction gratings.

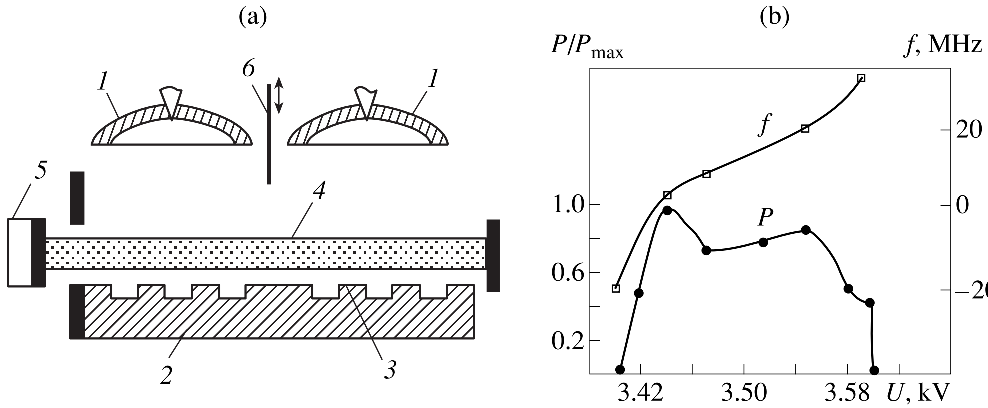

Fig. 6. A two-cascade DRO: (a) connection of cavities and (b) the oscillation range and the range of electron frequency tuning.

transmission band of a system where open cavities are placed in series. Importantly, the Q factor of a system of coupled open cavities is of the same order as the Q factors of isolated open cavities.

Thus, an open cavity coupled through strip diffraction gratings is preferable for the broadening of the transmission band of open cavity systems. Being implemented with the use of diffraction electronic devices, such a system is also characterized by the minimum overall sizes of an instrument along the axis of the electron flux.

4. APPLICATIONS OF COUPLED OPEN CAVITIES IN ELECTRONIC DEVICES

Figure 6a presents a diagram of a two-cascade DRO [5, 8] with open cavities placed in series with respect to the axis of the electron flux. Such a device includes a coupled open cavity consisting of two short-focal-length [10, 11] spherical mirrors *1* (R = 15 mm, A = 16 mm) and a common cylindrical mirror *2* (R = 110 mm) with a diffraction grating *3* oriented along the longitudinal axis of this mirror. An electron flux *4* is produced by a gun *5*. In the presence of a magnetic field, the electron flux moves along the diffraction grating, exciting oscillations in the open cavity. A screen *6*, which is employed to control the degree of coupling between the mirrors of the open cavity, can be shifted in the vertical plane.

In the case of weak coupling between open cavities, the considered device operates as a multifrequency oscillator at partial frequencies. In the case of optimal coupling, the considered system operates as a broadband DRO with coupled open cavities. If a microwave signal is applied to the input of the first (with respect to the gun) cascade and the beam current J is less than the triggering current J_n, then the device operates as an amplifier. These regimes were implemented in the millimeter wavelength range (f = 43–98 GHz). Figure 6b presents the oscillation area and the range of electron frequency tuning in the case of optimal coupling between the open cavities. The power of such a DRO at f = 84 GHz was equal to 0.4 W with the beam current equal to $J = 1.5J_n$ ($J_n \approx 30$ mA). The range of electron frequency tuning under these conditions was 1.5 times broader than in the case of a one-cascade DRO, which qualitatively correlates with the results of modeling of a system of coupled open cavities presented above (Fig. 3). A similar effect was also observed in the regime of amplification with $J \approx 0.8$–$0.9J_n$, which confirms the possibility of creating a regenerative amplifier based on coupled open cavities with a broader transmission band than in a single-cavity amplifier [13].

Figure 7 presents diagrams of electronic devices with open cavities placed in series with respect to the axis of the electron flux. An orotron shown in Fig. 7a [6] includes two coupled open cavities *1*. Each of these cavities consist of two mirrors *2* and *3*. Energy is coupled out through a waveguide in the case of mirrors *2*, while mirrors *3* have a shape of a parabolic cylinder. Strip diffraction gratings *4* located in the central sections of adjacent parabolic mirrors *3* are made of metal bars. A gun *5* employed to produce a converging electron flux *6* is placed between the parabolic mirrors *3*. A collector *7* is positioned in the area where the electron flux emerges from the interaction zone.

Operation of this orotron can be described in the following way. The gun and adjacent parabolic mirrors produce an initially converging electron flux. This flux experiences focusing within a small interaction length due to the spatial charge in the interaction zone formed by the open cavities and gratings. As electrons pass through the gap between diffraction gratings, diffraction radiation is produced in the open cavities. Electrons emerging from the interaction zone settle on the collector. If the electron flux current is much higher than the triggering current, then the orotron operates as an oscillator. Provided that a signal from some external source of microwave oscillations is applied to the input of one of the cavities and the condition of self-excitation is not satisfied, then the orotron operates as an amplifier. In addition, due to the presence of two cou-

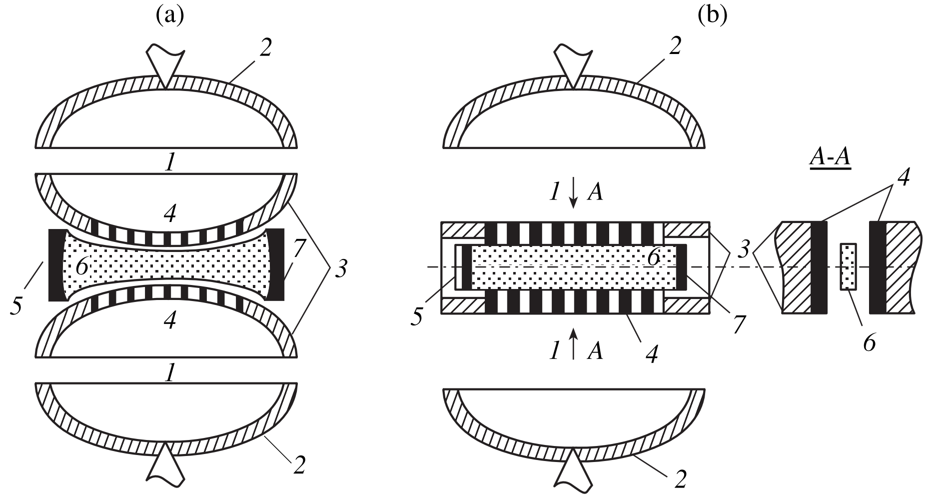

Fig. 7. Diagrams of electronic devices with parallel connection of open cavities: (a) an orotron with coupling through strip diffraction gratings and (b) DROs with coupling through reflective diffraction gratings.

pled open cavities, the orotron may also function as a frequency multiplier [7]. This device can be classified as a low-power radiation oscillator, since the increase of the electron flux current density is limited by the overheating of the strip diffraction grating.

Higher levels of the output power can be achieved with DROs based on coupled open cavities schematically shown in Fig. 7b. The design and the principle of operation of such a device are similar to the design and the principle of operation of the above-described orotron. However, cavities *1* in the considered device are coupled through the slits in two identical reflective diffraction gratings *4* located in the central sections of adjacent mirrors *3* and oriented perpendicular to the planes of these mirrors. The electron flux is focused with a magnetic field in this system. The use of massive gratings attached to mirrors allows the thermal regime of the device to be considerably improved and, consequently, electron fluxes with higher powers to be employed. Furthermore, one of the cavities in such a device may be implemented as a volume element with a moving short-circuiting piston located on the opposite side of the coupling slit. Figure 8 displays the dependences of the oscillation power and frequency for different distances h of the piston in the volume cavity in the case when the open cavity is tuned to the frequency f_0 = 36 GHz. As can be seen from these dependences, by mechanically tuning the volume cavity with a fixed value of H for the mirrors in the open cavity, one can smoothly tune the oscillation frequency within a sufficiently broad range with a jump in the level of the output power not exceeding 3 dB. This characteristic of the considered device indicates the possibility of improving the vibration stability of the system under consideration relative to the vibration stability of systems with mechanical frequency tuning by the mirrors of open cavities [5]. In addition, reflective DROs can be also created with the use of grating-coupled open cavities [14, 15]. In this case, the collector should be replaced by an electron reflector, producing an inverse electron flux. Such devices are characterized by low triggering currents and may operate in the regime of stochastic oscillations [16].

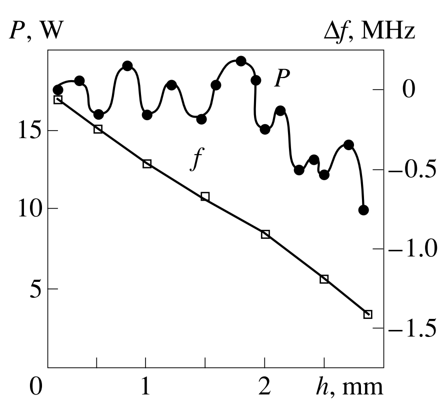

Fig. 8. Dependences of the oscillation power and frequency for a DRO with a tunable volume cavity coupled with the open cavity.

5. CONCLUSION

The studies of the electrodynamic properties of coupled open cavities presented in this paper have demonstrated that such systems allow the transmission band to be broadened as compared with transmission bands of isolated open cavities, permitting, at the same time, the Q factor to be kept at a high level. These results confirm the possibility of using coupled open cavities for the creation of such electronic devices as orotrons and DROs, which were proposed in earlier studies. Experiments with prototypes of these devices and the results of studies performed with some modifications of these systems indicate that devices of this type offer much promise for the creation of broadband oscillators and amplifiers in the millimeter and submillimeter wavelength ranges.

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