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THE RESONANT SYSTEM OF A SUB-TERAHERTZ LOCAL OSCILLATOR

Purpose. *The excitation efficiency is investigated of the first higher-order axially asymmetric oscillation mode (TEM_{10q}) excited in a hemispherical open resonator (OR) at the frequencies of the fundamental and second-order harmonics of the Gunn diode in the 4-mm and 2-mm wavelength ranges. The hemispherical resonator is coupled to its input waveguide via aperture-type coupling elements. The diameter 2a of the OR mirror apertures is 38 mm, while the curvature radius of the spherical reflector is R = 39 mm and the normalized distance between the mirrors is L/R = 0.593. Two aperture coupling elements of dimensions $a \times b$ = 6.9 × 9.6 mm are used to excite the OR. They permit controlling separately the functions of field-to-field matching (modes in the resonator and in the waveguide) and volume-to-volume coupling of the structural elements (the resonator and the waveguide). They are located at the center of the planar mirror. The field matching is determined by the geometric dimensions of the coupling elements, whereas the coupling matching is determined by the period of the one-dimensional E-polarized grating in their apertures. The Gunn diodes are used as generators, operating at the frequencies of the fundamental (75 GHz) andthe second-order (150 GHz) harmonics. The excitation efficiency of the TEM_{1011} oscillation in the OR of the geometry specified here, using aperture-type coupling elements as described, is 81.5%.*

Design/methodology/approach. *The excitation efficiency of higher-order oscillation modes TEM_{10q} in the OR being driven by an incident TE_{10} mode that arrives via two rectangular guides, is evalua-ted using the antenna surface utilization factor. The reflection coefficient from the OR and the loaded Q-factor are estimated in the familiar technique of partial reflection coefficients summation.*

Findings. *As has been shown, in an OR of parameters 2a = 38 mm, R = 78 mm, and L/R = 0.287 TEM_{1022} oscillations are excited at the frequency of the Gunn diode's second-order harmonic (i.e., 150 GHz) with an efficiency of 84%. In that same resonator, the excitation efficiency of the TEM_{1011} mode at the fundamental Gunn diode's harmonic (frequency of 75 GHz) equals 54%. By placing one-dimensional (E-polarized) wire gratings in the aperture of the coupling elements it proves possible to match the resonator with the waveguide. It has been found that in the case of a l = 0.2 mm spatial period of the wire grating and matched excitation of the resonator at f = 150 GHz (i.e. Γ150 = 0), the reflection coefficient Γ75 from the OR at f = 75 GHz equals 0.637. Upon excitation in the OR of oscillations in the TEM_{1022} mode, the total loss at f = 150 GHz is –1.23 dB. With TEM_{1011} oscillations excited in the same resonator at a frequency of 75 GHz, the total losses increase up to –5.4 dB.*

Conclusions. *The analysis has shown that an OR implementing the proposed method of excitation of higher-order axially asymmetric oscillation modes can be used for constructing a subterahertz range local oscillator. Moreover, such a resonant system may be considered both as a power combiner and a diplexer (filter).*

Keywords: *open resonator, aperture coupling element, rectangular waveguide, excitation efficiency, wire grating, oscillation Q-factor.*

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1. Introduction

Currently, there is an increased interest towards electromagnetic waves of the sub-terahertz and terahertz frequency ranges. The exploration of these ranges is expected to increase the rate of data transmission through communication systems and improve the spatial-and-temporal resolution of radar systems, as well as secrecy and noise immunity of the transmission process. At the same time, the weight and dimensions of the constituent structures, including antennas, could be substantially reduced.

In radar systems of the sub-terahertz range (at frequencies about 100–150 GHz) the role of local oscillators (LOs) is played by compact-sized solid-state generators capable of producing oscillations of high stability. However, at higher frequencies they become almost impractical due to the presence of parasitic reactances. In addition, the transit of current carriers through the region of their interaction with high frequency fields occurs over a finite time, which plays an increasingly noticeable negative role in such generators. This fundamental reason determines the high-frequency limit to the operation of solid-state sources as LOs for frequencies of 200–300 GHz.

One of the possible technical solutions that may allow overcoming the limit is to create single-stage generators of higher-order harmonics that would essentially make use of the nonlinearity shown by the dynamic voltage-current characteristics of Gunn diodes. High sensitivity LOs for super-heterodyne receivers of the sub-terahertz range can be conveniently constructed with Gunn diodes. While avalanche-transit time diodes are the most powerful solid-state sources at frequencies up to 300 GHz they demonstrate 10 to15 dB higher noise levels than Gunn diodes do[1].

Sources of the kind can generate synchronous oscillations not only at the fundamental frequency but also at the frequencies of higher-order harmonics, of which the second-order one is often in use, while the third-order harmonic is employed less frequently [2, 3]. In the extremely high frequency (EHF) range, the harmonic generator operates more efficiently at the second-order harmonic. In the case of higher-order harmonics, a combined generator circuit with a varactor multiplier becomes preferable [4]. The structural feature of the harmonic generator involving a Gunn diode is the presence of two circuits of which one is tuned to the fundamental frequency and the other to the harmonic frequency. The full circuit must necessarily include a diplexer (filter) to provide for separation of these oscillation frequencies. Another advantage of Gunn diode-based harmonic generators is the lower cost per unit power generated.

That is why considering the possibility of using an open resonator (OR) for the construction of solid-state sources of sub-terahertz heterodyne radiation is a task of practical interest. The correspondent resonant system can be viewed as a harmonic combiner on the one hand, or as a diplexer (filter) on the other.

2. The efficiency of exciting TEM_{10q} oscillations in an OR at fundamental harmonic frequencies of Gunn diodes

As has been shown in paper [5], the efficiency η of exciting the TEM_{10q} mode (expressed in terms of Hermit–Gaussian functions) in a hemispherical OR under the action of two fundamental TE_{10} modes which travel through two rectangular waveguides of cross section $a \times b$ (see Fig. 1*a*), can be expressed as

$$\eta = \frac{\pi^3}{2\tilde{a}^3\tilde{b}} \Phi^2\left(\frac{\tilde{b}}{2}\right) e^{-2\left(\frac{\pi}{2\tilde{a}}\right)^2} \times$$

$$\times\left[2 + e^{\left(\frac{\pi}{2\tilde{a}}\right)^2 - \tilde{a}^2}\left(W(g) + W^*(g)\right)\right]^2. \quad (1)$$

Here $\tilde{a} = a/w_0$ and $\tilde{b} = b/w_0$, with w_0 denoting the radius of the OR's fundamental (i.e., TEM_{00q}) oscillation's field spot on the particular mirror that carries the coupling elements; $\Phi\left(\tilde{b}/2\right)$ is the probability integral, and $W(g)$ is the probability integral of the complex argument $g = (\pi/2\tilde{a}) + j\tilde{a}^2$. The asterisk (*) denotes complex conjugation. To maximize the value of η (specifically, to obtain h = 0.866), normalized sizes of each of the two coupling elements should be $\tilde{a} = 1.669$ and $\tilde{b} = 1.98$.

To perform the analysis, we will choose an OR which was used in experimental studies in the four-millimeter wavelength range [5]. It was a hemispherical resonator with mirror apertures of 38 mm and spherical reflector of radius R = 39 mm. The dimensions of the two exciter elements located at the center of the flat mirror are $a \times b$ = 6.9 mm × 9.6 mm. Each of them is a pyramidal horn.

Similar coupling elements are known as aperture-type ones [6]. In this particular case, they are 85 mm in length, which value has been selected from the condition of obtaining a uniform phase distribution over the aperture (with a phase error less than 10°). The studies will be carried out at the frequency $f = 75$ GHz ($\lambda = 4$ mm) which corresponds to the fundamental harmonic of the 3A738N Gunn diodes [7].

In the case of hemispherical resonator geometry the principal (TEM_{00q}) mode reveals a maximum loaded Q-factor with $L_{00q}/R \approx 0.75$ (here L_{00q} is the separation between the mirrors supporting the TEM_{00q} oscillation) [8]. With an increase in the mode's transverse index, the normalized separation corresponding to a maximum loaded Q-factor will decrease. Accordingly, we tentatively assume L_{10q}/R=0.6 for the TEM_{10q} oscillation mode. With account of the wave's velocity factor in the resonator, this figure will correspond to a longitudinal oscillation index of $q = 11$.

For an oscillation in a hemispherical OR expressed in terms of the Hermite–Gauss functions the resonant frequency can be determined [9] from

$$f_{mnq} = \frac{c}{2L}\left(q + (m+n+1)\frac{1}{\pi}\arccos\sqrt{1-\frac{L}{R}}\right). \qquad (2)$$

Here $c = 3\times10^{11}$ m/s is the speed of light, and m and n are transverse oscillation indices. By making use of the above expression, we are in a position to improve the estimate for the efficient spacing between the resonator mirrors with regard to the fundamental oscillation mode TEM_{0011} (characterized by $f = 75$ GHz; $q = 11$; $m = n = 0$, and $R = 39$ mm). As it turned out, $L_{0011} = 22.55$ mm , or $L_{0011}/R = 0.578$. The radius w_0 of the oscillatory field spot on the plane mirror of the resonator can be calculated from

$$w_0 = \sqrt{\frac{\lambda}{\pi}R\sqrt{\frac{L}{R}\left(1-\frac{L}{R}\right)}} \qquad (3)$$

(see [9]). Upon substitution of the necessary numerical values into Eq. (3) we obtain $w_0 = 4.952$ mm. The normalized dimensions of the coupling elements in the case are $\tilde{a} = 1.393$ and $\tilde{b} = 1.939$. Next, we can find from Eq. (1) that the excitation efficiency η of the TEM_{1011} mode in a hemispherical OR of the above geometric dimensions, at the fundamental harmonic's frequency of the Gunn diodes, is 0.815 (under the effect of the two aperture-type exciter elements). This suggests that about 82 % of the power supplied to the resonator at 75 GHz is spent for exciting the first higher-order axially asymmetric oscillatory mode. Making use of Eq. (2), we can calculate the resonant spacing between the mirrors for the TEM_{1011} oscillation mode. For this case, $f = 75$ GHz, $q = 11$, $m = 1$, $n = 0$, and $R = 39$ mm. Upon substituting these numerical values into Eq. (2), we can find an equality to be fulfilled with $L_{1011} = 23.119$ mm (i.e., $L_{1011}/R = 0.593$). As can be seen, the estimate obtained for the normalized separation between the resonator mirrors for the oscillatory mode under analysis lies very closely to the initially adopted magnitude.

3. The excitation efficiency in the OR of the TEM_{10q} mode at second-order harmonic's frequencies of the Gunn diodes

Suppose now that the resonator is excited at the frequency of the second-order harmonic of the Gunn diodes 3A738N (specifically, $f = 150$ GHz). We assume that neither the distance between the resonator mirrors, nor the geometric dimensions of the coupling elements have changed. In this case we are, in fact, considering the TEM_{1022} mode as the wavelength has been halved down. In order to retain on the plane cavity mirror the previous value of the field spot radius w_0 of the main TEM_{0022} oscillation, it would be necessary to at least double up the curvature radius of the spherical reflector. This follows from Eq. (3). Proceeding from. Eq. (2), let us refine the estimate for the resonance spacing between the mirrors in the case of the fundamental mode (i.e., $f = 150$ GHz; $q = 22$; $m = n = 0$, and $R = 78$ mm). Upon substitution of the numerical values into Eq. (2), we find $L_{0022} = 22.179$ mm. Now, from. Eq. (3) we arrive at $w_0 = 4.733$ mm. As can be seen, the value obtained for the field spot radius of the TEM_{0022} oscillatory mode existing at the second harmonic frequency of the Gunn diodes is close to such of the TEM_{0011} mode at the fundamental harmonic's frequency of the same diodes with $R = 39$ mm, namely $w_0 = 4.952$ mm. In the case under discussion, the sizes of the coupling elements are $\tilde{a} = 1.458$ and $\tilde{b} = 2.028$. Making use of Eq. (1), we find the excitation efficiency for the TEM_{1022} mode in a hemispherical resonator of the given dimensions to be equal to 0.837. This suggests that about 84 % of the power supplied to the resonator at the second harmonic's frequency of the two Gunn diodes gets spent to excite the TEM_{1022} oscillatory mode. Approximately the same amount of power, but at the frequency of the fundamental harmonic, is used to excite the TEM_{1011} mode in the above considered resonator.

Like in the previous case, we can use Eq. (2) for calculating the resonant distance between the mirrors

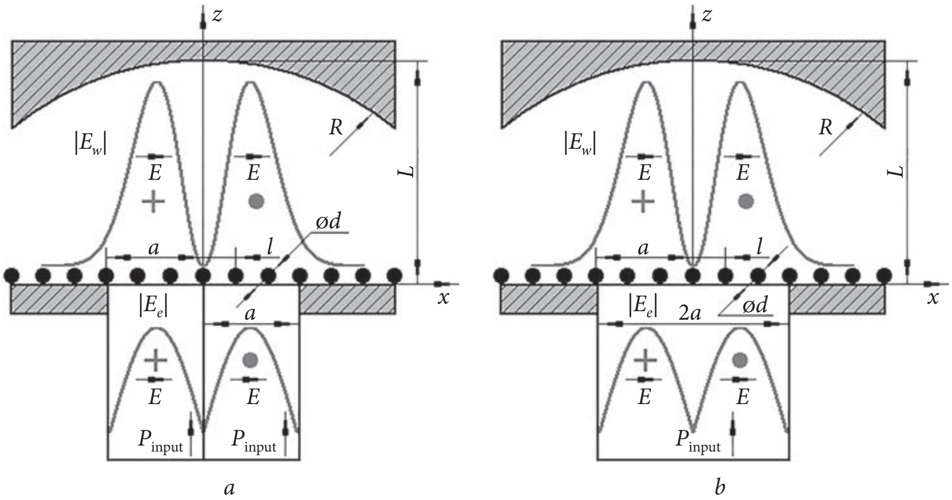

Fig. 1. Hemispherical OR, excited by two (*a*) or one (*b*) rectangular waveguides

for the oscillation under consideration (specifically, $f = 150$ GHz; $q = 22$, $m = 1$; $n = 0$, and $R = 78$ mm). Upon substituting the given values into Eq. (2) we find the equality to be fulfilled with $L_{1022} = 22.36$ mm (i.e., $L_{1022}/R = 0.287$).

It is also of practical interest to evaluate the excitation efficiency of the TEM_{1011} mode at the fundamental harmonic's frequency of a resonator of given dimensions. As follows from Eq. (2), the distance L_{0011} between the mirrors that would be necessary for efficiently exciting the oscillatory mode TEM_{0011} (with parameters $f = 75$ GHz; $q = 11$; $m = n = 0$, and $R = 78$ mm) equals 22.36 mm. Next, making use of these values for f, L_{0011} and R we find from Eq. (3) that $w_0 = 6.701$ mm. In this case $\widetilde{a} = 1.03$ and $\widetilde{b} = 1.433$. Then, according to Eq. (1), the efficiency η of exciting the TEM_{1011} mode at the fundamental harmonic's frequency of the Gunn diodes (driven through two coupling elements (see Fig. 1*a*)) equals 0.54. This calculationindicates that in this case only 54 % of the power penetrating into the resonator at the fundamental harmonic's frequency of the Gunn diodes is used to excite the TEM_{1011} oscillatory mode.

A distinctive feature of the aperture-type coupling elements is that they permit separating the functions of field matching (the oscillation field $|E_w|$ in the resonator and the wave field $|E_e|$ in the waveguide, see Fig. 1) and coupling matching (the resonator and the waveguide). The excitation efficiency of the higher-order modes TEM_{1011} and TEM_{1022} in resonators of specific geometric dimensions at the frequencies of the fundamental ($f = 75$ GHz) and second-order ($f = 150$ GHz) harmonics of the Gunn diodes has been discussed above. The amount of coupling between the OR and its waveguide feeds is controlled with the help of one-dimensional, *E*-polarized diffraction gratings [10]. These are located in the openings of the aperture-type coupling elements (see Fig. 1*a*). By properly selecting the character and amount of coupling between the OR and the waveguides, it may prove possible not only to reduce the excitation losses in the resonator, but also to significantly improve its selective properties. Therefore, as the next step, we will analyze the effect of one-dimensional diffraction gratings on the coupling of the resonators and their waveguide feeds.

4. Effect of diffraction grating parameters on the waveguide-to-resonator coupling at the fundamental harmonic's frequency of the Gunn diodes

To find the reflection coefficient from a resonator, we resort to the technique of summing partial reflection coefficients from the one-dimensional diffraction grating [11]. For the sake of simplicity, we will consider excitation of the resonant TEM_{10q} mode (see Fig. 1*b*, $|E_w|$) in a hemispherical OR by the guided mode TE_{20} traveling through a coupled rectangular waveguide (see Fig. 1*b*, $|E_e|$). The width of the larger wall of such an oversized rectangular waveguide is $2a$ (see Fig. 1*b*). The excitation efficiency of the TEM_{10q} mode in the OR by means of this waveguide shall be identical to the efficiency of exciting this resonant mode through the use of two rectangular waveguides of larger wall's width a (see Fig. 1*a*) [12]. Let us write

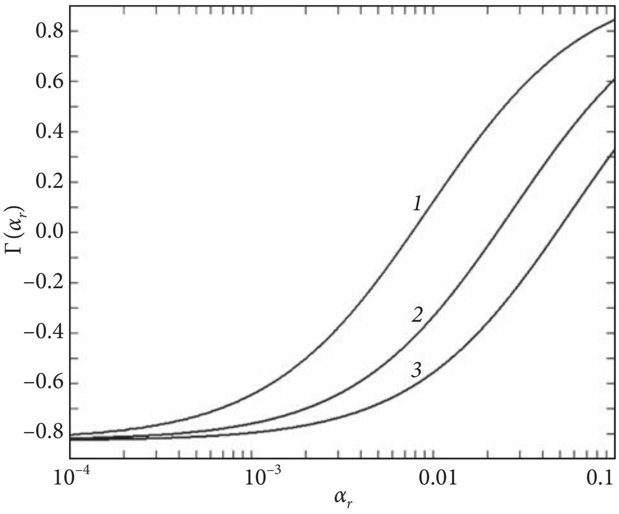

Fig. 2. Reflection coefficients Γ from the OR at $f = 75$ GHz in dependence on the resonance loss parameter α_r, plotted for various periods l of the diffraction grating

down the ratio defining the resonant reflection coefficient Γ from an OR [13],

$$\Gamma = |r_1| - \frac{|t_1|^2 |r_2| S_e S_r^2}{1 - |r_1||r_2| S_r^2}. \qquad (4)$$

Here $|r_1|$ and $|t_1|$ stand for absolute magnitudes (moduli) of the reflection and transmission coefficients, respectively, from the wired diffraction grating (of *E*-polarization) with a variable period *l*. The grating is placed in the aperture of the rectangular waveguide of width 2*a* at the center of the OR's plane mirror (see Fig. 1*b*). They are related as $|r_1|^2 + |t_1|^2 = 1$ [14]. The parameter $|r_2|$ in Eq. (4) is the modulus of the reflection coefficient from the spherical mirror which is assumed to be equal to 1. The parameters $S_e = \exp(-\alpha_e/2)$ and $S_r = \exp(-\alpha_r/2)$ are field transfer coefficients during one way transit of the wave from one mirror to the other which are determined by the losses for excitation, $\alpha_e = P_e/P_{res} = 1 - \eta$, and resonant losses $\alpha_r = \alpha_d + \alpha_{oh} = (P_d + P_{oh})/P_{res}$. The value P_e is the power loss which in the general case is the total of the losses caused by spillover of power beyond the edges of one of the cavity mirrors and the losses resulting from unmatched excitation of oscillations in the OR. The magnitudes P_d and P_{oh} denote, respectively, the diffractional and ohmic losses of power, while P_{res} stands for the power supplied to the OR through the coupling element at the moment of resonance. Admittedly, P_{oh} is determined exclusively by the power loss due to unmatched excitation, whereas the resonant losses in the OR are determined by the ohmic losses P_{oh}. The reason is that the efficiency η has been calculated on the assumption of infinite mirror apertures [5].

Fig. 2 shows the reflection coefficient given by Eq. (4), in dependence on the resonance loss parameter α_r, for a variety of diffraction grating periods *l*. The wire gratings in the aperture of the oversized waveguide are of periods $l = 0.3$ mm (curve *1*); $l = 0.4$ mm (curve *2*), and $l = 0.5$ mm (curve *3*).

The oscillations excited in the resonator belong to the first higher-order axially asymmetric mode, namely TEM_{1011} (realized with $L_{1011} = 23.119$ mm). All the gratings are wound with tungsten wire of diameter $d = 0.02$ mm. The curves have been plotted for the fundamental harmonic frequency of the Gunn diodes (i.e., $f = 75$ GHz) and with $S_e = 0.912$. The correspondent excitation efficiency η for the oscillation mode TEM_{1011} in the OR of the above quoted geometry ($R = 39$ mm) is $h = 0.815$. The absolute magnitudes (moduli) of reflection from the gratings coefficients can be calculated as [10]

$$|r_1| = \frac{1 - k_0^2 l_0 l_2}{\sqrt{(1 + k_0^2 l_0^2)(1 + k_0^2 l_2^2)}}, \qquad (5)$$

where $k_0 = 2\pi/\lambda$, $l_0 = (l/\pi)\ln(l/2\pi d)$, and $l_2 = \pi d^2/l$.

As can be seen from Fig. 2, the general run of the calculated reflection coefficient Γ plotted in dependence on the resonance loss parameter α_r is in a qualitative agreement with the experimentally measured coefficient of reflection from the hemispherical OR. (This later dependence was taken in the course of decrease in the distance *L/R* between the reflectors [15]). In this case the field spots on the mirrors get smaller in size and, as a result, the α_r parameter gets smaller too. If the period of the one-dimensional grating placed in the waveguide aperture of width 2*a* (see Fig. 1*b*) is increased, the regime of matched propagation (i.e., Γ = 0) is reached at higher resonant loss values, specifically $\alpha_r = 7.693 \times 10^{-3}$ with $l = 0.3$ mm (curve *1*); $\alpha_r = 2.258 \times 10^{-2}$ with $l = 0.4$ mm (curve *2*), and $\alpha_r = 4.803 \times 10^{-2}$ with $l = 0.5$ mm (curve *3*). As follows from our calculations, in the case of OR mirrors embodied as fine-finished copper surfaces, a matched coupling regime at the fundamental harmonic frequency of the Gunn diodes can be realized through the use of gratings of greater density.

There is one more point to note. The output power of each of the two 3A738N Gunn diodes, shown at the fundamental frequency is 20 mW [7]. Suppose, the diodes are located in the regions of maximum electric field strength $|E_e|$ of the TE_{20} waveguide mode (see Fig. 1*b*). The wire diffraction grating placed in the aperture of the rectangular waveguide of width $2a$ has a period l equal to 0.4 mm, which is 0.1 of the operating wavelength. In the case just considered, the waveguide was matched to the resonator (i.e., $\Gamma = 0$) with $\alpha_r = 2.258\times10^{-2}$ (see Fig. 2, curve *2*). Experimental studies have shown that the power summation factor for two Gunn diodes in an OR excited by two aperture-type coupling elements (see Fig. 1*a*) can reach 0.9. Hence, the power spent to excite the TEM_{1011} mode in the resonator will be, with account of the excitation efficiency, $40\times0.9\times0.815 = 29.34$ (mW). As can be seen, the power loss associated with excitation in the resonator of the TEM_{1011} oscillations at the fundamental harmonics' frequency of the Gunn diodes was only $10\lg(29.3/40) = -1.35$ dB.

Let us consider the dependences of the resonators' loaded Q-factors, Q_L, on the grating transmission coefficients $|t_1|$. In order to do that, we write down the expression that defines Q_L [11, 13],

$$Q_L = \frac{2k_0L\sqrt[4]{1-t_1^2}\,S_r}{1-\sqrt{1-t_1^2}\,S_r^2}. \tag{6}$$

In the above expression, we can take $|r_2| = 1$ with an accuracy sufficient for practical purposes. The resonator is of hemispherical geometry, with a 38 mm mirror apertures, as described above, and a 39 mm curvature radius R of the spherical reflector. The resonator is excited at the fundamental harmonic's frequency of the Gunn diodes, $f = 75$ GHz. The oscillation mode is TEM_{1011} (with $L_{1011} = 23.119$ mm). Here, as before, we consider excitation of the TEM_{1011} resonator mode by the TE_{20} waveguide mode, propagating along a rectangular waveguide with a larger wall of width $2a$ (see Fig. 1*b*). These dependences are shown in Fig. 3 for three values of resonance losses corresponding to different cases of resonator to waveguide matching for a variety of grating periods, namely $\alpha_r = 7.693\times10^{-3}$ (curve *1*, $l = 0.3$ mm); $\alpha_r = 2.258\times10^{-2}$ (curve *2*, $l = 0.4$ mm), and $\alpha_r = 4.803\times10^{-2}$ (curve *3*, $l = 0.5$ mm).

With $|t_1|\to 0$ the the resonator to waveguide coupling Q will tend to infinity. Accordingly, Q_L will be determined by Q_0, the proper Q-factor of the resonator, which depends on the resonance losses only. As can be seen from Fig. 3, the value of Q_0 drops down at

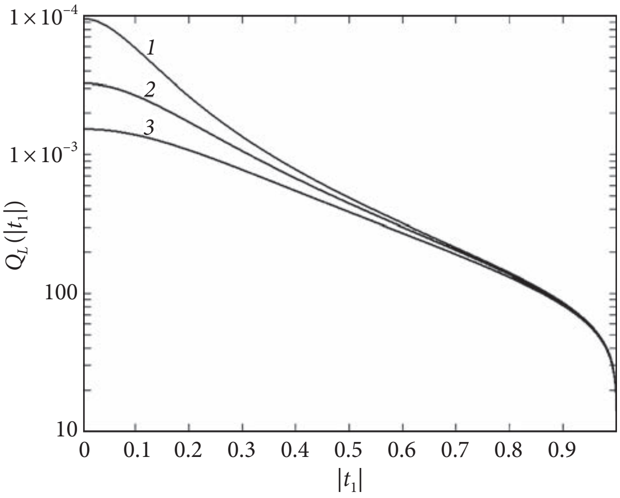

Fig. 3. Loaded Q-factors of the OR at $f = 75$ GHz in dependence on the grating transmission coefficient, for different periods of the coupling element in the aperture

higher resonance losses. Indeed, with $|t_1| = 0$, we can read $Q_0 = 9.4\times10^3$ from curve *1*; $Q_0 = 3.2\times10^3$from curve *2*, and $Q_0 = 1.5\times10^3$ from curve *3*. At greater values of $|t_1|$ the difference in the values of the loaded Q-factor, shown for specific resonance losses, becomes less pronounced. This is due to the fact that in the case of weak coupling $(|t_1| \le 0.5,\ |r_1| \ge 0.866)$ (which corresponds to the use of dense gratings), the loaded Q-factor of the OR (denoted Q_L)is determined mainly by the proper Q-factor, Q_0. That depends solely on the magnitude of resonance losses. With an increase in the grating transmission coefficient $(|t_1| \ge 0.5)$, the loaded Q-factor of the resonator will be determined by Q_C, i.e. the resonator-to-waveguide coupling factor, while variations in the resonance losses will have but little effect on Q_L.

Let us estimate the loaded Q-factor of a resonator involving a wire grating of period $l = 0.4$ mm (see Fig. 3, curve *2*) in the aperture of a rectangular coupling element of width $2a$. Making use of Eq. (5) we obtain that with $\lambda = 4$ mm (i.e., $f = 75$ GHz) and $d = 0.02$ mm $|r_1|$ equals 0.9731. Then $|t_1| = 0.2304$, and one can find from Fig. 3 that $Q_L = 1.4\times10^3$

5. Effect of diffraction grating parameters on the resonator-to-waveguide coupling at the second harmonic's frequency of the Gunn diodes

Now consider a resonator that is excited at the second harmonic's frequency of the Gunn diodes (i.e., $f = 150$ GHz). Once again, apertures of the mirrors

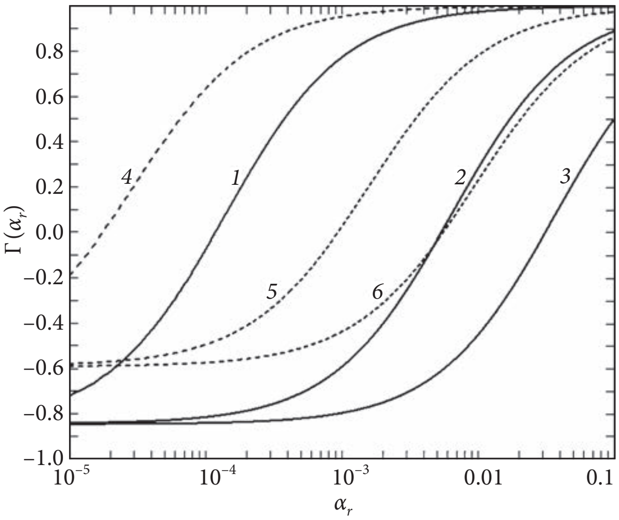

Fig. 4. Reflection coefficients from the OR in dependence on the resonant loss parameter: A few different wire gratings in the apertures of the coupling elements (frequency $f = 150$ GHz)

and the separation between them, as well as the geometry and dimensions of the coupler all remain the same. Still, the curvature radius of the spherical mirror has been increased up to $R = 78$ mm. The result is that the TEM_{1022} mode is excited in the resonator (with $L_{1022} = 22.36$ mm).

Fig. 4 shows the dependences of the reflection coefficient (as determined from Eq. (4)) upon the resonance losses parameter α_r, for various periods l of the wire diffraction gratinigs (E-polarized) placed in the aperture of the rectangular waveguide. Specifically, the values are $l = 0.1$ mm (solid curve *1*); $l = 0.2$ mm (solid curve *2*), and $l = 0.3$ mm (solid curve *3*). The gratings have been wound of tungsten wire of diameter $d = 0.02$ mm. The excitation efficiency of the TEM_{1022} mode in the resonator can be estimated as $h = 0.837$ (with $S_e = 0.922$). To simplify the analysis, we assume, as before, that the resonator is excited by a TE_{20} waveguide mode propagating through a rectangular waveguide. The guide of larger wall width $2a$ is connected to the resonant cavity in the middle of its plane mirror (see Fig. 1*b*). The moduli $|r_1|$ of reflection coefficients from diffraction gratings of different periods are calculated after Eq. (5).

Once again, it can be clearly seen from the figure that the calculated dependences $\Gamma = Y(a_r)$ are in good agreement with the experimentally measured dependences $\Gamma = F(L/R)$. At greater periods of the wire grating sitting in the aperture of the oversized rectangular waveguide the regime of matched propagation (i.e., $\Gamma = 0$) sets in with higher values of the resonance loss parameter, for example $\alpha_r = 1.181\times10^{-4}$ with $l = 0.1$ mm (solid curve *1*); $\alpha_r = 5.346\times10^{-3}$ with $l = 0.2$ mm (solid curve *2*), and $\alpha_r = 3.097\times10^{-2}$ at $l = 0.3$ mm (solid curve *3*).

The same figure carries three dashed curves plotted for $f = 75$ GHz. The geometric dimensions of the resonator remained the same. For the resonator under consideration, the excitation efficiency η for the TEM_{1011} mode (at the fundamental harmonic's frequency of the Gunn diodes) is $h = 0.54$ ($S_e = 0.795$). The dashed curve *4* describes reflection from the resonator in dependence on the resonance loss parameter α_r, for the case of grating period $l = 0.1$ mm (E-polarized wire grating). When the resonator is matched with the waveguide ($\Gamma = 0$) at the second harmonic's frequency of the Gunn diode (i.e., $f = 150$ GHz), the reflection coefficient at the fundamental frequency is $\Gamma = 0.678$ (with $\alpha_r = 1.181\times10^{-4}$). The dashed curve *5* represents the reflection coefficient from the resonator *versus* resonant losses for a grating of period $l = 0.2$ mm sitting in the aperture of the coupling element. If the resonator is matched with the waveguide (hence, $\Gamma = 0$) at $f = 150$ GHz, the reflection coefficient Γ at $f = 75$ GHz is 0.637 (with $\alpha_r = 5.346\times10^{-3}$). The dashed curve *6* represents the reflection coefficient as a function of the resonant loss parameter α_r for a wire grating (E-polarized) of period $l = 0.3$ mm. In this case, when the resonator is matched to the waveguide ($\Gamma = 0$) at the second harmonic's frequency of the Gunn diodes, the reflection coefficient Γ at $f = 75$ GHz equals 0.63 (with $\alpha_r = 3.097\times10^{-2}$).

We have already mentioned that the output power of each of the two Gunn diodes 3A738N demonstrated at the fundamental harmonic frequency is 20 mW. The aperture of the oversized rectangular waveguide involves a wire diffraction grating of period $l = 0.1\,\lambda$, where λ is the operating wavelength, so for $f = 150$ GHz we have $l = 0.2$ mm. At $f = 150$ GHz the resonator-to-waveguide matching ($\Gamma = 0$) is reached with $\alpha_r = 5.346\times10^{-3}$ (see Fig. 4, solid curve *2*). Recall that the correspondent reflection coefficient Γ_{75} at $f = 75$ GHz is 0.637. Consequently, the power supplied to the OR at the moment of resonance (oscillation mode TEM_{1011}) is $P_{transmitted} = P_{incident}\times(1-|\Gamma|^2) = 40\times(1-0.637^2) = 23.77$ mW. Once again, the summation coefficient in the OR for the powers from the two Gunn diodes will be considered equal to 0.9. So, with account of the excitation efficiency, the power necessary for exciting in the resonator an oscillation at $f = 75$ GHz is $23.77\times0.9\times0.54 =$

= 11.55 (mW). Now we can estimate the power loss during excitation of the TEM_{1011} mode in the resonator of the above dimensions. The figure proves to be 10lg(11.55/40) = –5.4 dB. Thus, we have significantly reduced the signal level at 75 GHz (the Gunn diodes' fundamental harmonic) compared with the previous case, owing to a correct choice of the electrodynamic system's dimensions. Now consider resonator operation at f = 150 GHz. As shown in paper [16], the power level of the Gunn diode's output at the n-th harmonic behaves as $P_{out} \approx 1/n$. Next, the power at the said frequency arriving to the OR from two Gunn diodes, via a single matched rectangular waveguide connected in the middle of the resonator's planar mirror (see Fig. 1*b*), has been estimated as 20 mW. Taking into account the power summation coefficients pertinent to the two Gunn diodes in the resonator and the excitation efficiency of the oscillation considered, we find the power necessary for exciting the axially asymmetric mode TEM_{1022} to be $20 \times 0.9 \times 0.837$ = 15.07 (mW). As can be seen, the resonator of the dimensions described spends a greater fraction of the power it has been fed with for exciting oscillations at the frequency of the second-order harmonic of the Gunn diodes than for the TEM_{1011} oscillatory mode at f = 75 GHz. The total loss associated with excitation of the TEM_{1022} oscillation type in the resonator will be 10lg(15.07/20) = –1.23 dB. This value is even lower than the loss accompanying excitation in the OR of the TEM_{1011} mode at the fundamental frequency of the Gunn diodes.

In case the power level achieved happens insufficient for solving specific practical problems, then two T-junctions can be used in the system. Due to that it would be possible to provide a nearly fourfold increase in the power supplied to the resonator from four Gunn diodes through two aperture coupling elements.

Consider the dependences shown by the resonator's loaded Q-factors, Q_L, on the transmission coefficients $|t_1|$ of the gratings. To that end, one can use Eq. (6). We consider the TEM_{1022} oscillation type of the resonator (L_{1022} = 22.36 mm). The mirror apertures are, as above, are equal to 38 mm, and the curvature radius of the spherical reflector is R = 78 mm. The resonant frequency is f = 150 GHz. The pertinent numerical results are shown in Fig. 5. The curves are plotted for three values of resonance losses corresponding to cases of full resonator-to-waveguide matching (i.e., Γ = 0) achievable with diffraction gratings of different periods l (see Fig. 4): $\alpha_r = 1.181 \times 10^{-4}$ (curve *1*,

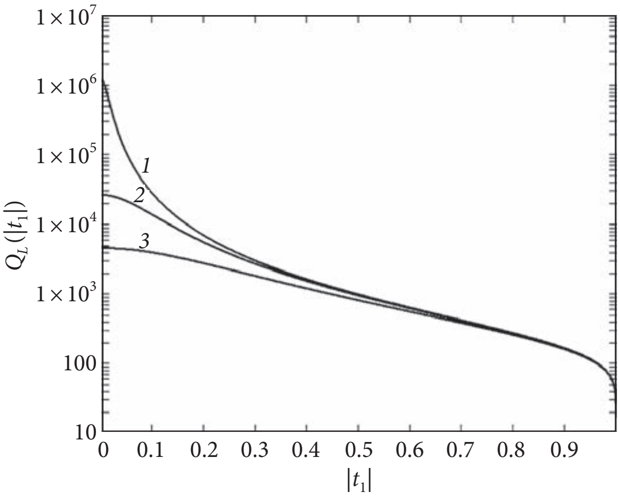

Fig. 5. Loaded Q-factors of the OR at f = 150 GHz in dependence upon the transmission coefficient $|t_1|$ of wire gratings of different spatial periods l. The gratings are placed in the aperture of the OR-waveguide coupling element: *1* — l = 0.1 mm; *2* — l = 0.2 mm, and *3* — l = 0.3 mm. At higher values of the resonance losses in the OR, Q_0 drops down. With $\alpha_r = 5.346 \times 10^{-3}$ (and $|t_1|$ = 0) the proper Q-factor is 2.6×10^4 (see curve *2* in Fig. 5), and with $\alpha_r = 3.097 \times 10^{-2}$ the value is $Q_0 = 4.5 \times 10^3$ (curve *3*)

l = 0.1 mm); $\alpha_r = 5.346 \times 10^{-3}$ (curve *2*, l = 0.2 mm), and $\alpha_r = 3.097 \times 10^{-2}$ (curve *3*, l = 0.3 mm).

Should $|t_1|$ decrease, the quality factor Q_C characterizing the resonator-to-feed waveguide coupling will tend to infinity. Therefore, at $|t_1| = 0$ Q_L will be determined by Q_0 alone, i.e. the resonator's proper Q-factor which, in turn, depends upon resonance losses only. As can be seen from Fig. 5, at $|t_1| = 0$ the proper Q-factor of a low-loss resonator (specifically, one with $\alpha_r = 1.181 \times 10^{-4}$) reaches $\approx 1.2 \times 10^6$ (curve *1*).

With non-zero values of the gratings' transmission coefficient $|t_1|$ the difference in the values of the loaded Q-factors of the OR at fixed resonance losses manifests itself in different ways. In the case of weak coupling $(|t_1| \le 0.5,\ |r_1| \ge 0.866)$ the loaded Q-factor Q_L of the OR is determined mainly by the proper value Q_0 which is dependent solely on the magnitude of the resonance losses. So, a change in these latter may lead to a significant change in the loaded Q-factor. At higher values of the transmission coefficient $|t_1|$ $(|t_1| \ge 0.5,\ |r_1| \le 0.866)$, Q_L will be determined by Q_C, the resonator-to-waveguide coupling Q-factor, such that changes in resonance losses will have but little effect on the magnitude of Q_L.

Let us estimate the loaded Q-factor of a resonator involving, in the aperture of a rectangular coupling element, an *E*-polarized wire grating of period $l = 0.2$ mm (see Fig. 5, curve *2*). The oscillation type excited in the OR is TEM_{1022}. The estimate for $|r_1|$ following from Eq. (5) for $\lambda = 2$ mm (i.e., $f = 150$ GHz) and $d = 0.02$ mm is $|r_1| = 0.9937$. With $|t_1| = 0.1122$ and $L_{1022} = 22.36$ mm we find from Fig. 5 a loaded *Q*-factor like $Q_L = 1.2 \times 10^4$. This value is about 8 times higher than the loaded *Q*-factor of the resonator supporting the TEM_{1011} mode at $f = 75$ GHz (specifically, $Q_L \approx 1.46 \times 10^3$). The reason lies in the constructive differences, namely that in the latter case $R = 39$ mm and the aperture of the rectangular coupler involves a one-dimensional wire grating of period $l = 0.4$ mm. Consequently, at $f = 150$ GHz one can obtain a better frequency stability and a higher power summation factor, which is of great practical importance when constructing local oscillators (LO) for the sub-terahertz frequency range. In addition, the high *Q*-factor of the resonant system may allow greatly reducing the phase noise in the signal from the LO [17]. Moreover, the minimum phase noise of the LO is achieved when the loaded *Q*-factor of the resonator equals one half of the proper *Q*, i.e. $Q_L = Q_0/2$ [18]. This corresponds to full matching, $\Gamma = 0$, between the resonator and the feeding waveguide. By properly selecting parameters of the one-dimensional, *E*-polarized wire grating placed in the aperture of the oversized rectangular coupling element (see Fig. 1*b*), one should be able to always ensure matched excitation of the resonator at the second harmonic's frequency of the Gunn diodes, as well as a minimum phase noise in the LO signal.

6. Conclusions

The research carried out allows us to draw a number of important practical conclusions.

1. By properly selecting geometric dimensions of the OR and of the aperture-based coupling elements, it proves possible to ensure a high excitation efficiency (up to 84%) for the higher-order axially asymmetric oscillation type TEM_{1022} at the second harmonic's frequency of the Gunn diodes employed. At the same time, the excitation efficiency for the TEM_{1011} oscillation type, realizable at the fundamental harmonic's frequency, with two diodes and the same geometric dimensions of the OR, will be significantly lower (namely, 54%).

2. By placing one-dimensional, *E*-polarized wire gratings of high density, with spatial periods *l* equal to 0.1, 0.2, and 0.3 mm into the aperture of the oversized rectangular waveguide, it proves possible to achieve good matching ($\Gamma = 0$) between the resonator and its feeding waveguide at the second harmonic's frequency of the Gunn diodes. In this case the OR exhibits high coefficients of reflection from the one-dimensional wire gratings at the frequency of the diodes' fundamental harmonic, specifically $\Gamma = 0.678$ with $l = 0.1$ mm; $\Gamma = 0.637$ with $l = 0.2$ mm, and $\Gamma = 0.63$ with $l = 0.3$ mm. This is of great practical importance for designing a local oscillator of sub-terahertz range. With a proper choice of parameters of the one-dimensional wire gratings which sit in the apertures of the coupling elements the resonator may represent a diplexer (filter).

3. The use of dense gratings can lead to a significant increase of the loaded *Q*-factor of the open resonator in its matched regime if the OR is excited at the second harmonic's frequency of the Gunn diodes. Thus, with a $l = 0.2$ mm period of the *E*-polarized one-dimensional wire grating the loaded *Q* is $Q_L = 1.2 \times 10^4$. In its turn, the increased loaded *Q*-factor allows increasing the power summation coefficient at the Gunn diodes' second harmonic, also providing for a better frequency stability and reducing the level of phase noise. This has a positive effect when the OR is used as a resonant system for a sub-terahertz local oscillator.

4. An optimal choice of the geometry and dimensions of the electrodynamic system for the local oscillator of the sub-terahertz range will ensure the resonator-to-waveguide matching and efficient excitation of the axially asymmetric oscillation mode at the frequency of the Gunn diodes' second-order harmonics. The accompanying power losses at the frequency of Gunn diodes' second-order harmonic are estimated as −1.23 dB. Thus the suppression of the signal at the frequency of the fundamental harmonics of the diodes without additional absorbing devices will be at least −5.4 dB.

5. The studies conducted have shown that an OR which is excited by aperture-type coupling elements at the frequency of the second-order harmonic of 4-mm range Gunn diodes can serve as a basis for constructing a local oscillator of the sub-terahertz range. The OR can be an effective power adder for several Gunn diodes, thus increasing the power output from the local oscillator. In addition, an advantage of such a LO is the lower per unit cost of the generated power.

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РЕЗОНАНСНА СИСТЕМА ГЕТЕРОДИНА СУБТЕРАГЕРЦОВОГО ДІАПАЗОНУ ЧАСТОТ

Предмет і мета роботи. Дослідження особливостей збудження першого вищого аксіально-несиметричного типу коливань TEM_{10q} у відкритому резонаторі (ВР) у 4-та 2-мм діапазонах довжин хвиль. Напівсферичний резонатор включений у хвилевідну лінію передачі. Апертури дзеркал резонатора (розмір $2a$) дорівнюють 38 мм, радіус кривизни сферичного відбивача $R = 39$ мм, нормована відстань між дзеркалами $L/R = 0.593$. Для збудження ВР використовуються два апертурні елементи зв'язку з розмірами $a \times b = 6.9 \times 9.6$ мм, що розташовані в центрі плоского дзеркала. Особливість таких елементів зв'язку полягає в тому, що вони дозволяють розділити функції узгодження за полем (коливання в резонаторі й хвилевідна мода) і за зв'язком елементів структури (резонатор і хвилевідний тракт). Узгодження за полем визначається геометричними розмірами елементів зв'язку, а узгодження за зв'язком—періодом одновимірної E-поляризованої решітки в їх розкривах. В якості генераторів використовуються діоди Ганна, що працюють на частотах основної (75 ГГц) і другої (150 ГГц) гармонік. Ефективність збудження коливання TEM_{1011} у ВР зазначеної вище геометрії за допомогою апертурних елементів зв'язку становить 81.5 %.

Методи та методологія. Для визначення ефективності збудження в резонаторі вищого коливання типу TEM_{10q} за допомогою моди TE_{10}, що надходить з двох прямокутних хвилеводів, застосовується коефіцієнт використання поверхні антени. Коефіцієнт відбиття від ВР та навантажена добротність визначаються за допомогою відомого методу підсумовування парціальних коефіцієнтів відбиття від резонансної системи.

Результати. Показано, що у ВР з параметрами $2a = 38$ мм, $R = 78$ мм, $L/R = 0.287$ мода TEM_{1022} збуджується з ефективністю 84 % на частоті другої гармоніки діодів Ганна, що дорівнює 150 ГГц. У цьому ж резонаторі ефективність збудження моди TEM_{1011} складає 54% на частоті основної гармоніки діодів Ганна, тобто 75 ГГц. За допомогою одновимірних, E-поляризованих дротяних решіток, що розташовуються в розкривах апертурних елементів зв'язку, можна узгодити резонатор з хвилеводним трактом. Встановлено, що при застосуванні дротяної решітки з періодом $l = 0.2$ мм і узгодженому збудженні резонатора на частоті 150 ГГц ($\Gamma_{150} = 0$) коефіцієнт відбиття Γ_{75} від ВР на частоті 75 ГГц складає вже 0.637. Сумарні втрати при збудженні моди TEM_{1022} у ВР зазначеної вище геометрії на частоті 150 ГГц становлять –1.23 дБ. При збудженні в цьому ж резонаторі моди TEM_{1011} на частоті 75 ГГц сумарні втрати зростають до –5.4 дБ.

Висновки. Виконані дослідження показали, що ВР із запропонованим апертурним способом збудження вищих аксіально-несиметричних типів коливань можна використовувати для побудови гетеродина субтерагерцового діапазону частот. Таку резонансну систему можна розглядати одночасно як суматор потужності і як діплексер (фільтр).

Ключові слова: *відкритий резонатор, апертурний елемент зв'язку, прямокутний хвилевід, ефективність збудження, дротова решітка, добротність коливання.*