

Power Summation in an Open Resonator with Aperture Coupling Elements

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ABSTRACT The paper considers the power summation of two sources in a hemispherical open resonator (OR). A scheme with an *E*-tee waveguide was used. The study was carried out in the four-millimeter wavelength range. In the resonator, the first highest axially asymmetric TEM_{10q} mode is excited with the help of aperture coupling elements. The coupling elements are pyramidal horns located in the center of a flat mirror, with apertures of 6.9×9.6 mm and a length of 85 mm. There are one-dimensional *E*-polarized diffraction gratings with periods of 0.2 mm, 0.4 mm, and 0.6 mm in the apertures of the coupling elements. It is shown that the maximum power summation coefficient of two sources in an OR using aperture coupling elements, in the apertures of which a one-dimensional diffraction grating with a period of 0.6 mm is located, is 90%. The high excitation efficiency in the resonator of the TEM_{10q} mode, with the help of aperture coupling elements, ensures the angular selection of the oscillation spectrum of such a resonant system. It has been established that to sum the powers of two sources in the OR, it is advisable to use not the TEM_{10q} mode but TEM_{20q} .

INDEX TERMS powers summation, open resonator, excitation efficiency, transmission coefficient, aperture coupling element, loaded *Q*-factor, one-dimensional diffraction grating

I. INTRODUCTION

In work [1], studies were carried out on the power summation of two sources in a hemispherical open resonator (OR) included in a waveguide transmission line. With the help of two slot coupling elements located on a flat mirror, the first highest axially asymmetric TEM_{10q} mode is excited in the resonator. It is shown that the summation coefficient, in this case, does not exceed 72%. A similar result was obtained in [2], which showed that the power summation coefficient of two sources removed from the OR volume at a frequency of 94 GHz is 79%. The main oscillation-type TEM_{00q} is excited in the resonator.

Currently, a large number of works are known that consider the power summation of the Gunn diodes in the OR, both in the millimeter [3-7] and centimeter [8-10] wavelength ranges.

All of the above designs of power adders have one common drawback. Diodes with current leads [3,5,7] are located on the surface of one of the mirrors [5], or in grooves [4,9,10] made on its surface. They can also be located between the lamellas of an *H*-polarized diffraction grating, which is located in the cavity volume [3,7]. In some cases, a microstrip grating is placed on the surface of the resonator mirror, under which Gunn diodes are installed [6,8]. Additional diffraction losses occur in such a resonant system due to the comparable geometric dimensions of all these elements with the operating wavelength, not to mention additional ohmic losses. These losses lead to a decrease in the loaded *Q*-factor of the resonant system and, as a consequence, to a decrease in the efficiency of power summation of individual sources in the resonant volume.

The most typical value of the power summation factor of individual sources located in the OR volume is about 70% [8].

The location of individual sources in a common resonant volume leads to a strong coupling between them. This causes difficulties in setting up such power adders and makes such systems critical to the spread of parameters of individual sources, even with a small number of them. In turn, measures aimed at eliminating these phenomena lead to a significant complication in the design of the circuit itself for adding individual sources into a single resonant volume [11]. Therefore, more promising, as shown in [12], are systems for power summation of individual sources that are located outside the resonant volume. In this case, the connection between the active elements will be weaker than in schemes for power summation of sources located in a resonant volume [13,14]. Thanks to this, circuits for power summation of individual sources removed from the resonant volume [1,2] are characterized by ease of setup and low criticality to the spread of parameters of active elements.

When excitation of oscillations in an OR using slot coupling elements, part of the power is always emitted into free space [15]. This is because the width of the directional pattern of the slotted coupling element, made on one of the resonator mirrors, is always wider than the aperture of the opposite mirror. This radiation will not only affect the connection of the resonator with the waveguide transmission line but also lead to additional losses for such a resonant system. Sometimes, an OR must be used on a metal screen. This applies to those cases when it is necessary to work with high power levels: when summing

the powers of several magnetrons in the resonator; when building compressors of electromagnetic impulses [16] based on OR. A metal screen will thicken the oscillation spectrum due to the excitation of additional modes in such a resonant system [17]. Another disadvantage of the slotted excitation method is the difficulty in creating an OR with predetermined values of the reflection or transmission coefficients. Therefore, when using a resonator as part of a waveguide transmission line, it is advisable to use the aperture method of excitation of oscillations in the OR [18].

The main advantage of this excitation method of oscillations in the resonator is that it makes it possible to separate the matching functions over the field and the coupling. By choosing the geometric dimensions of the coupling elements in a certain way, it is possible to match the structures of the exciting E_e (waveguide wave) and working E_w (mode of the resonator) fields. The connection of the resonator with the waveguide transmission line is controlled by the parameters of one-dimensional E -polarized diffraction gratings located in the openings of the aperture coupling elements. Due to reducing radiation losses, such coupling elements should provide a higher powersummation factor of individual sources in the OR. The polarization wire gratings are also used in several devices and circuits in the higher frequency region [19], for example, in the scheme of a Michelson polarization interferometer [20]. Instead of a waveguide tee and waveguide elements, a polarization grating was used, installed in a quasi-optical beam splitter together with functional elements based on a hollow dielectric beam guide.

On the other hand, with the aperture method of excitation of the modes in the resonator, the spectrum's angular selection should occur. Therefore, considering the powers summation of two sources in a hemispherical OR is of practical interest. With the help of aperture coupling elements, the first highest axially asymmetric TEM_{10q} mode is excited in the resonator. This work is devoted to the study of this issue.

II. EXPERIMENTAL STAND

The block diagram of the experimental stand, with the help of which studies were carried out on the powersummation of individual sources in a hemispherical OR, is described in detail in [1]. The main element of the stand is an E -tee waveguide, which allows you to study the powers summation of the two sources in the OR using one generator, the frequency of which is 74.935 GHz ($\lambda=4.003$ mm). All elements included in the scheme are the same as in the specified work. The radius of curvature R of spherical mirror 22 with two slotted coupling elements is 39 mm (Fig. 1). Only a flat mirror with coupling elements differs. As before, the aperture of this mirror is 38 mm. There are two aperture coupling elements (Fig. 1), which are pyramidal horns located symmetrically with respect to the resonator axis. Their geometric dimensions in the plane of the mirror are 19 mm (Fig. 2). The lengths of such coupling elements 18 are 85 mm (Fig. 3). The numbers II

and III in Fig. 1 indicate the arms of the E -tee waveguide (Fig. 1, [1]).

All designations in Fig. 1 are the same as in work [1]. Here, the number 18 designates two aperture coupling elements. Their apertures contain one-dimensional E -polarized diffraction grating 26. It is a metal ring with an outer diameter of 50 mm, an inner diameter of 40 mm, and a height of 5 mm. On this ring, a grating is wound with a tungsten wire with a diameter of 0.02 mm (Fig. 3).

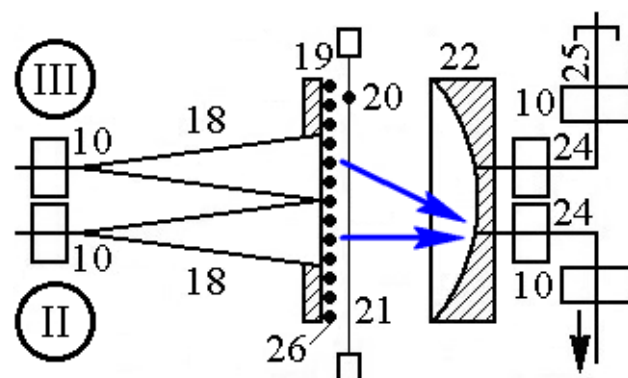


FIGURE 1. OR with aperture coupling elements.

It is known that to obtain a high value of the surface utilization factor (SIF) of reflector antennas, it is necessary to match the fields in the focal plane of the reflector and the aperture of the irradiator [21]. From a physical viewpoint, this is analogous to the matching of the resonator field with the field of a wave propagating along a waveguide located at the center of a flat mirror.

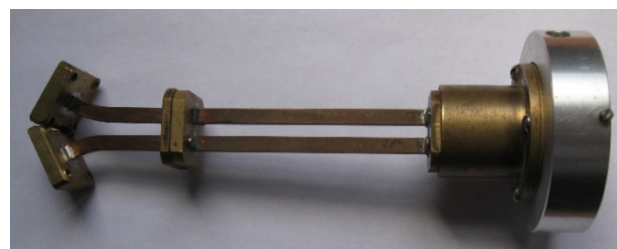


FIGURE 2. Flat resonator mirror with aperture coupling elements.

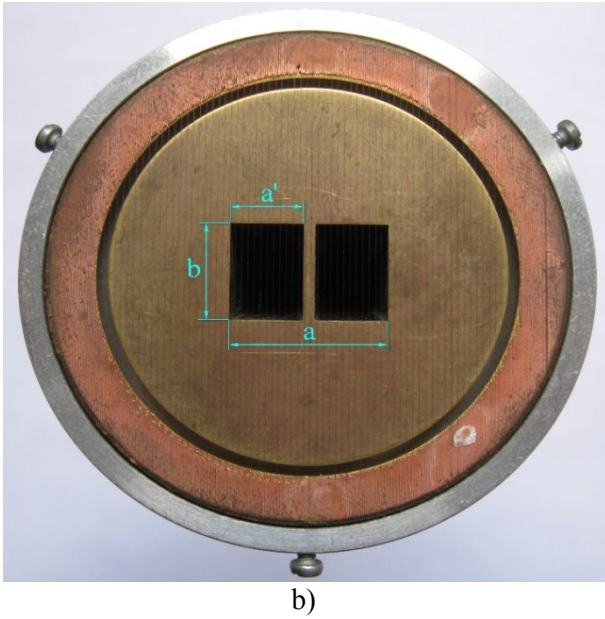


FIGURE 3. Flat resonator mirror with E - polarized diffraction grating.

In view of the above, let us determine the excitation efficiency η of the first higher axially asymmetric TEM_{10q} mode in a hemispherical OR using a rectangular waveguide with a section $a \times b$ (Fig. 3). The waveguide is located at the center of the flat mirror, and the TE_{20} wave propagates along it. To do this, the relation [21] was used

$$\eta = \frac{\left| \int_{-a/2}^{a/2} \int_{-b/2}^{b/2} \vec{E}_e(x, y) \vec{E}_w^*(x, y) dx dy \right|^2}{\left\| \vec{E}_e(x, y) \right\|^2 \left\| \vec{E}_w(x, y) \right\|^2}. \quad (1)$$

After substituting into (1) the expressions that determine the electrical component of the field of the TE_{20} wave in the waveguide ($\vec{E}_e$) and the electrical component of the field of the TEM_{10q} mode in the OR ($\vec{E}_w$), we obtain [22]

$$\eta = \frac{4\pi^3}{\tilde{a}^3 \tilde{b}} \Phi^2 \left(\frac{\tilde{b}}{2} \right) e^{-2 \left(\frac{\pi}{\tilde{a}} \right)^2} \left[2 + e^{\left(\frac{\pi}{\tilde{a}} \right)^2 - \left(\frac{\tilde{a}}{2} \right)^2} \left(W(g) + W^*(g) \right) \right]^2. \quad (2)$$

Here $\tilde{a} = a/w_0$, $\tilde{b} = b/w_0$, $\Phi(\tilde{b}/2)$ —probability integral; $W(g)$ —probability integral of a complex argument; $g = (\pi/\tilde{a}) + j(\tilde{a}/2)$, w_0 — the spot radius of the field of the main OR TEM_{00q} mode on that resonator mirror, in the center of which a rectangular waveguide with a section $a \times b$ is made. The calculations showed that the maximum excitation efficiency of the considered mode using the TE_{20} waveguide wave is 0.867 at $\tilde{a} = 3.338$ and $\tilde{b} = 1.98$ [22]. If a metal plane is placed in the center of a rectangular waveguide with a section $a \times b$ (Fig. 3), we will get two rectangular waveguides with a section $a' \times b$. In each of these waveguides, the main TE_{10} waveguide wave will propagate. In this case, the maximum excitation efficiency of the TEM_{10q} mode in the OR with the help of such a wave will be $\eta = 0.4335$ at the size of a rectangular aperture of $\tilde{a}' \times \tilde{b} = 1.669 \times 1.98$.

With the help of two rectangular waveguides of the indicated dimensions, the modes excitation efficiency will

double and coincide with the value of η given above. As can be seen, in any case, the excitation efficiency of the TEM_{10q} mode in the OR is high ($\sim 87\%$). Due to low radiation losses ($\sim 13\%$), this should lead to an angular selection of the resonator oscillation spectrum for the considered method of excitation of the TEM_{10q} mode.

As mentioned above, the lengths of two horn emitters 18 (Fig. 1) equal 85 mm. It is well known that the maximum phase error $\psi_{\max}$ in the opening of a pyramidal horn is determined by its geometric dimensions. At the same time, its admissible value must satisfy the following conditions [23]. In the plane of $\vec{H}$ vector of the fundamental wave TE_{10} of a rectangular waveguide

$$\psi_{\max}^H = \frac{\pi a'^2}{4\lambda R_H} \leq \frac{3}{4}\pi, \quad (3)$$

and in the plane of the vector $\vec{E}$ of the same waveguide wave

$$\psi_{\max}^E = \frac{\pi b^2}{4\lambda R_E} \leq \frac{\pi}{2}. \quad (4)$$

In expressions (3), (4), R_H and R_E - distance from the opening to the point where the edges of the pyramidal horn converge in the planes H и E , respectively. For a rectangular waveguide with a cross-section of 3.6×1.8 mm and an aperture size of 6.9×9.6 mm, $R_H = 92.727$ mm, $R_E = 19.615$ mm. After substituting numerical values into expressions (3) and (4), we will ensure they are fulfilled for the used aperture coupling elements. So, in the plane of the vector $\vec{H}$ $\psi_{\max}^H = 0.101 < 2.356$, in the plane of the $\vec{E}$ vector $\psi_{\max}^E = 0.922 < 1.571$. When conducting experimental studies on the power's summation of individual sources in a hemispherical OR, one-dimensional E -polarized diffraction gratings with periods ℓ , equal to 0.2 mm, 0.4 mm, and 0.6 mm. As mentioned above, all gratings are wound with tungsten wire 0.02 mm in diameter.

III. STUDY OF THE POWERS SUMMATION IN OR

At the first stage, as in work [1], in arm II of the E -tee waveguide, after the waveguide bend 14 in the E -plane and waveguide twist 12, matched load 23 is located. A short-circuiting piston 25 is connected to the output of a segment of a rectangular waveguide 10, which is included in this part of the waveguide path and connected to the coupling element 18 (Fig. 1, [1]). In the openings of both aperture coupling elements, there is a one-dimensional E -polarized diffraction grating 26 (Fig. 1). The grating period is 0.2 mm. Let us consider the excitation in the resonator of the first higher axially asymmetric TEM_{10q} mode using one aperture coupling element 18. The results of measuring the resonant transmission coefficient $K_{transm}^{(II)}$ with a decrease in the normalized distance L/R between the OR mirrors are shown in Fig. 4 (curve 2). In this case, as in the case of excitation of the same mode in the OR using a slot coupling element, the resonator transmission coefficient increases as the distance between the mirror's L/R decreases from 0.916 to 0.702. This is due to a decrease in losses for such a resonant system. With a further reduction in L/R , $K_{transm}^{(II)}$ almost

does not change. In this case, the diffraction losses become small, and the losses in the resonator are determined mainly by the ohmic losses. The maximum value, equal to 0.22, is reached by the OR transmission coefficient at $L/R=0.224$ (TEM₁₀₄ mode). A decrease $K_{transm}^{(III)}$ to a value of 0.2 takes place with a semi-confocal resonator geometry ($L/R=0.491$). This is because, in this case, the considered TEM₁₀₉ mode interacts with another axially asymmetric TEM₃₀₉ mode of the resonator. The decrease in $K_{transm}^{(III)}$ for the TEM₁₀₆ mode ($L/R=0.331$) is due to the interaction with some other higher mode, which could not be identified.

Let's change the scheme of the experimental setup. Now matched load 23 is located in arm III of the *E*-tee waveguide (Fig. 1, [1]). Short-circuiting piston 25 is connected to the output of a section of rectangular waveguide 10, which enters this part of the waveguide path and is connected to coupling element 18 (Fig. 1, [1]). The resonator is excited through the second aperture coupling element connected to the waveguide path connected to arm II of the *E*-tee waveguide (Fig. 1). The measurement results are shown in Fig. 4 (curve 3).

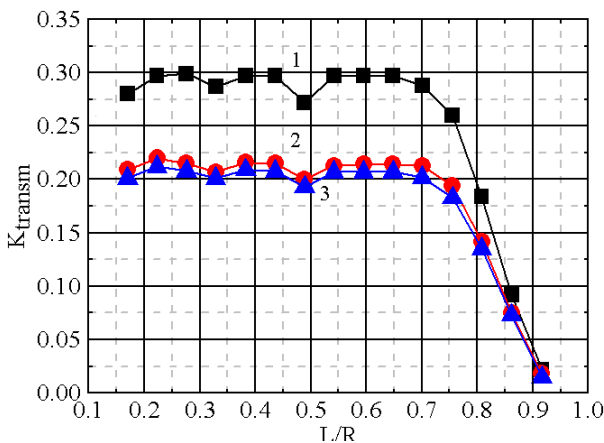


FIGURE 4. Dependences of K_{transm} on L/R for OR at a period of the *E*-polarized diffraction grating in openings of aperture coupling elements equal 0.2 mm.

The figure shows that the behavior $K_{transm}^{(II)}$ repeats the behavior $K_{transm}^{(III)}$ when L/R decreases. The difference is that over the entire range of variation of the distances between the resonator mirrors, it is $K_{transm}^{(II)}$ less than $K_{transm}^{(III)}$. So, at $L/R=0.383$ (TEM₁₀₇ mode) $K_{transm}^{(III)}=0.216$, $K_{transm}^{(II)}=0.209$. Their difference for the indicated modes is 0.007. When the resonator is excited through arm II of the *E*-tee waveguide, the maximum value $K_{transm}^{(II)}=0.212$ for the same TEM₁₀₄ mode with the same distance between the OR mirrors $L/R=0.224$. The difference between the values of the resonant transmission coefficients for this L/R between the OR mirrors is 0.008.

Now, we will excite in the resonator the first highest axially asymmetric TEM_{10q} mode with two aperture coupling elements (Fig. 1). The behavior of the resonant transmission coefficient $K_{transm}^{(I)}$ with a change in the normalized distance L/R between the OR mirrors is shown in Fig. 4 (curve 1). From the above figure, it is easy to see that the resonant transmission coefficient $K_{transm}^{(I)}$ behaves

similarly to the behavior $K_{transm}^{(II)}$ and $K_{transm}^{(III)}$ in the entire resonator tuning range. Only in this case, the resonant transmission coefficient becomes significantly higher due to the excitation of the considered mode in the OR with the help of two coupling elements. In the tuning range, $L/R=0.224\div0.649$ $K_{transm}^{(I)}=0.297$, except for two points. At $L/R=0.491$, the decrease in $K_{transm}^{(I)}$, as mentioned above, is associated with the interaction of the TEM₁₀₉ mode with the TEM₃₀₉ mode. In the case of $L/R=0.331$, the resonant transmission coefficient decreases because, in this case, the TEM₁₀₆ mode interacts with another higher mode.

Let's place a one-dimensional *E*-polarized diffraction grating with a period $\ell=0.4$ mm in the openings of the aperture coupling elements. As in the previous case, the grating is a tungsten wire 0.02 mm in diameter. We will not repeat the measurement procedure $K_{transm}^{(II)}$ and $K_{transm}^{(III)}$ for the TEM_{10q} mode excitation in the OR. It is described in detail above. The measurement results are shown in Fig. 5. Curve 2 shows the behavior of the resonant transmission coefficient $K_{transm}^{(III)}$ as the normalized distance L/R between the OR mirrors decreases. In this case, the resonator is excited through arm III of the *E*-tee waveguide (Fig. 1). As we can see, as L/R decreases from 0.916 to 0.542, the resonant transmission coefficient of the resonator increases. As mentioned above, this is associated with a decrease in diffraction and ohmic losses for the TEM_{10q} mode. With a further decrease in the distance between the resonator mirrors from 0.542 to 0.277, it practically does not change $K_{transm}^{(III)}$ and remains equal to 0.24. The exception is the value $L/R=0.491$, which corresponds to the semi-confocal geometry of the OR. Here, as above, the TEM₁₀₉ mode interacts with the TEM₃₀₉ mode. In this case, $K_{transm}^{(III)}=0.203$. As the period of the one-dimensional *E*-polarized diffraction grating 26 (Fig. 1) increases, the transmission coefficient through it increases [24]. Therefore, the resonator K_{transm} increases (curves 2, Fig. 4,5). In this case, the amplitudes of all excited modes in the resonator grow [18]. The main reason for this is the increase in the connection of the modes excited in the OR with the input waveguide 10. As in the previous case, consider the TEM₁₀₇ mode ($L/R=0.383$). For this mode $K_{transm}^{(II)}=0.24$.

Now, we will excite the resonator through arm II of the *E*-tee waveguide (Fig. 1). During measurements, matched load 23 is located in the arm III of the *E*-tee waveguide (Fig. 1, [1]). In Fig. 5, number 3 denotes a curve that describes the behavior $K_{transm}^{(II)}$ when changing the distance between the OR mirrors. As you can see, the behavior of the resonant transmission coefficient with a change in L/R practically repeats the behavior of curve 2. As the resonant distance between the mirrors decreases from 0.916 to 0.542, the $K_{transm}^{(II)}$ increases since the diffraction and ohmic losses reduce for the TEM_{10q} mode we are considering. In the range of L/R from 0.542 to 0.277, $K_{transm}^{(II)}$ remains equal to 0.226. With a normalized distance between the mirrors equal to 0.491, $K_{transm}^{(II)}=0.195$. This is the semi-confocal geometry of the OR. The figure shows that, as in the case of a thicker grating ($\ell=0.2$ mm), curve 3 goes below curve 2. Let's consider the same TEM₁₀₇ mode ($L/R=0.383$). In this case, $K_{transm}^{(II)}=0.226$. The difference in resonant

transmission coefficients for the TEM_{107} mode (curves 2,3) has increased and is 0.014.

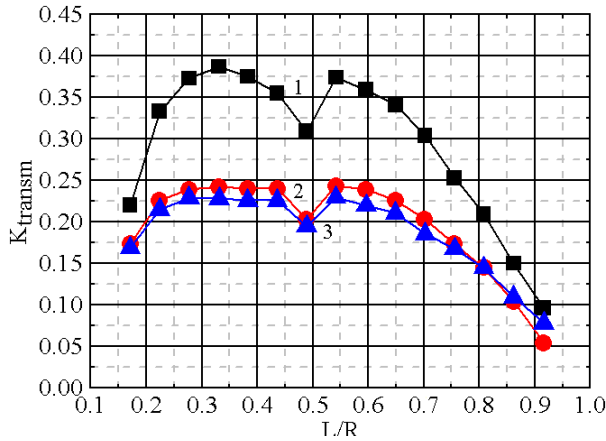


FIGURE 5. Dependences of K_{transm} on L/R for OR at a period of the E -polarized diffraction grating in openings of aperture coupling elements equal 0.4 mm.

Let us now consider the excitation in the OR of the considered mode with the help of two aperture coupling elements (Fig. 1). How $K_{transm}^{(I)}$ behaves when changing L/R is shown in Fig. 5 (curve 1). In the entire range of change L/R , $K_{transm}^{(I)}$ repeats the behavior of $K_{transm}^{(II)}$ and $K_{transm}^{(III)}$. As can be seen from the figure, the resonant transmission coefficient becomes significantly higher due to the excitation of the TEM_{10q} mode in the OR with the help of two coupling elements. The decrease in $K_{transm}^{(I)}$ to 0.309 at $L/R=0.491$ corresponds to the semi-confocal resonator geometry. Here, the TEM_{109} mode interacts with the TEM_{309} mode. The maximum value equal to 0.387 $K_{transm}^{(I)}$ reached at $L/R=0.331$. An increase in the period of a one-dimensional E -polarized diffraction grating in the openings of aperture coupling elements from 0.2 mm to 0.4 mm leads to a significant increase in the maximum value $K_{transm}^{(I)}$ from 0.297 to 0.387.

Now, in the openings of both coupling elements, we place a one-dimensional E -polarized diffraction grating with a period of $\ell=0.6$ mm (Fig. 3). This grating, like the previous ones, is wound with tungsten wire 0.02 mm in diameter. The results of measuring the resonant transmission coefficients are shown in Fig. 6. First, let's consider the behavior $K_{transm}^{(III)}$ with a change in the normalized distance L/R between the OR mirrors (curve 2). The resonator is excited through arm III of the E -tee waveguide (Fig. 1). It can be seen from the figure that an increase in the coupling between the resonator and the input waveguide leads to a change in the behavior of the curve. As L/R decreases from 0.916 to 0.487, the resonant transmission coefficient of the resonator grows. Now, the interaction of the TEM_{10q} mode with other modes occurs at $L/R=0.434$ (this is the TEM_{108} mode, $K_{transm}^{(III)}=0.256$) and at $L/R=0.222$ (this is the TEM_{104} mode, $K_{transm}^{(III)}=0.243$). The maximum value equal to 0.312 $K_{transm}^{(III)}$ reached at $L/R=0.168$. If it were not for the interaction with other modes, then the resonant transmission coefficient increases over the entire range of decreasing the distance between the OR mirrors. This is observed only

the case of the considered sparse diffraction grating, the period of which is $\ell>0.1\lambda$.

As the next step, we will excite the resonator through arm II of the E -tee waveguide. The behavior of $K_{transm}^{(II)}$ is shown in Fig. 6 (curve 3). As can be seen, the course of this curve completely repeats the course of curve 2. But curve 3, as in the two cases considered above, goes below curve 2. Consider again the TEM_{107} mode ($L/R=0.383$). In this case, $K_{transm}^{(III)}=0.262$, and $K_{transm}^{(II)}=0.24$. The difference in the values of the resonant transmission coefficients is 0.022. The interaction of the TEM_{10q} mode with other modes excited in the OR also takes place at $L/R=0.434$ (this is the TEM_{108} mode, $K_{transm}^{(II)}=0.234$) and at $L/R=0.222$ (this is the TEM_{104} mode, $K_{transm}^{(II)}=0.18$). The maximum value equal to 0.257 $K_{transm}^{(II)}$ reached $L/R=0.168$.

Now, we will excite the resonator through two aperture coupling elements 18. The results of measurements of the resonant transmission coefficient for the TEM_{10q} mode with a change in L/R are shown in Fig. 6 (curve 1). The general behavior of $K_{transm}^{(I)}$ with a change in the distance between the OR mirrors repeats the behavior of curves 2 and 3. But in this case, the curve of the dependence of the resonant transmission coefficient on the distance between the resonator mirrors goes much higher. As L/R decreases from 0.916 to 0.487, $K_{transm}^{(I)}$ grows. The considered TEM_{10q} oscillation interacts with other oscillations types of the resonator at $L/R=0.434$ (TEM_{108} mode, $K_{transm}^{(I)}=0.4$) and at $L/R=0.222$ (TEM_{104} mode, $K_{transm}^{(I)}=0.29$). The maximum value equal to 0.498 $K_{transm}^{(I)}$ reached at $L/R=0.327$.

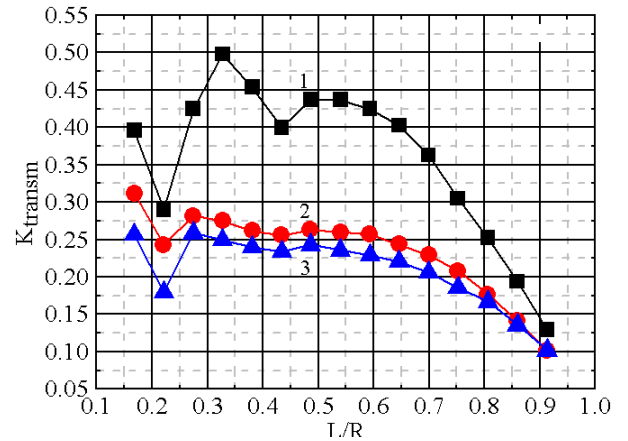


FIGURE 6. Dependences of K_{transm} on L/R for OR at a period of the E -polarized diffraction grating in openings of aperture coupling elements equal 0.6 mm.

Let us estimate the behavior of the power summation factor of two sources K_{summ}^2 with a change in the distance between the resonator mirrors. To find the power summation factor, we use the formula $K_{summ}^2 = [K_{transm}^{(I)}]^2 / [K_{transm}^{(II)2} + K_{transm}^{(III)2}]$. The calculation results are shown in Fig. 7. It can be seen from the figure that the general behavior K_{summ}^2 for all three periods of one- E -polarized diffraction gratings in the openings of dimensional the aperture coupling elements with a change in L/R is approximately the same. The greater the period of the

diffraction grating ℓ in the openings of the coupling elements, the greater K_{summ}^2 .

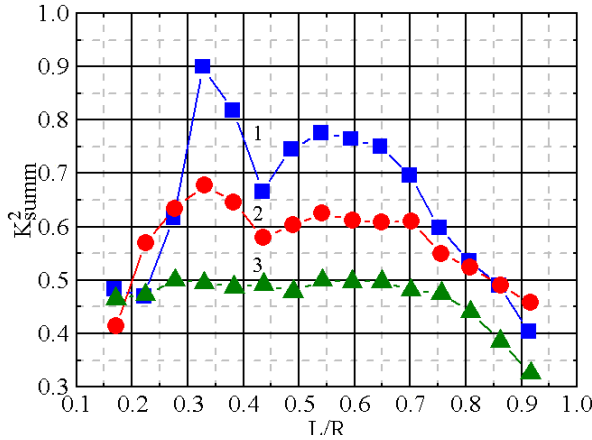


FIGURE 7. Dependences of K_{summ}^2 on L/R for different periods of E -polarized gratings in the openings of the aperture coupling elements.

For $\ell=0.2$ mm, the power summation factor of two sources reaches the maximum values equal to 0.5 at $L/R=0.542$ (TEM₁₀₁₀ mode) and $L/R=0.276$ (TEM₁₀₅ mode) (curve 3). A dip in this curve takes place at $L/R=0.491$ (TEM₁₀₉ mode), which corresponds to the semi-confocal geometry of the OR. With an increase in the period ℓ of one-dimensional diffraction grating to 0.4 mm, the maximum values K_{summ}^2 are 0.625 ($L/R=0.542$, TEM₁₀₁₀ mode) and 0.678 ($L/R=0.331$, TEM₁₀₆ mode) (curve 2). In the case of a further increase in the period of one-dimensional diffraction grating to 0.6 mm, the maximum values of the power summation coefficient for the two separate sources increase to 0.776 and 0.9 at $L/R=0.542$ (TEM₁₀₁₀ mode) and $L/R=0.331$ (TEM₁₀₆ mode) (Fig. 7, curve 1). The dips in curves 1 and 2 ($L/R=0.434$) are associated with an increase in the connection of all modes excited in the OR with the leading waveguide paths. In [1], it has been shown that with the slotted method of excitation of the TEM_{10q} mode in the OR, the maximum K_{summ}^2 is 0.719 at $L/R=0.596$ (TEM₁₀₁₁ mode) and $L/R=0.384$ (TEM₁₀₇ mode). Thus, the aperture method of excitation of the TEM_{10q} mode in the OR makes obtaining a higher powers summation factor of two separate sources possible. In this case, sparse E -polarized diffraction gratings must be used to control the connection with the input waveguides.

It is of practical interest to measure the loaded Q -factors Q_L of OR with aperture coupling elements, in the openings of which various one-dimensional E -polarized diffraction gratings are located. To do this, we use the technique described in [1]. It was also shown that upon excitation in the resonator of the TEM₁₀₁₁ mode ($L/R=0.596$) with the help of two slot couplers, $Q_L=528$. Therefore, let's estimate the loaded Q -factors of the TEM₁₀₁₁ mode in the considered OR ($L/R=0.595$). As it turned out, at $\ell=0.2$ mm $Q_L=1658$, at $\ell=0.4$ mm $Q_L=749$, and at $\ell=0.6$ mm $Q_L=453$. The decrease in the loaded Q -factor of the same mode with an increase in the period of a one-dimensional grating is associated with a decrease in the Q -factor of the coupling

between the OR and the waveguide paths. Thus, even a rare grating with a period $\ell=0.6$ mm in the tuning band $L/R=0.3\div0.67$, except for the point $L/R=0.434$ (Fig. 7, curve 1), ensures the powers summation factor of the two sources is higher than in the case excitation of the resonator by two slotted coupling elements.

It was said above that the matched excitation of the TEM_{10q} mode in the OR should lead to the angular selection of the oscillation spectrum. In our resonator, as shown by measurements $K_{transm}^{(II)}$ and $K_{transm}^{(III)}$, other higher modes are also excited in addition to the considered mode. Therefore, consider the OR oscillation spectrum section. A one-dimensional E -polarized diffraction grating with a period of 0.6 mm is located in the openings of the aperture coupling elements (Fig. 3). This grating was chosen because, due to the strong coupling with the input waveguides, the maximum number of modes [25] should be excited in the resonator. Let's consider a part of the OR oscillation spectrum containing the TEM₁₀₁₁ mode, for which we measured Q_L . The measurement results are shown in Fig. 8.

From the above figure, we see that the angular selection of the oscillation spectrum takes place in the resonator. In the OR, the TEM_{10q} mode is excited. Along with the considered mode, the highest axially asymmetric TEM_{40q} mode is excited in the resonator. It was said above that the excitation efficiency of the TEM_{10q} mode in the resonator can reach 87% for specific sizes of aperture coupling elements. Therefore, it is of interest to evaluate the excitation efficiency of the η TEM₁₀₁₁ mode in the OR using the two considered aperture coupling elements (Fig. 3).

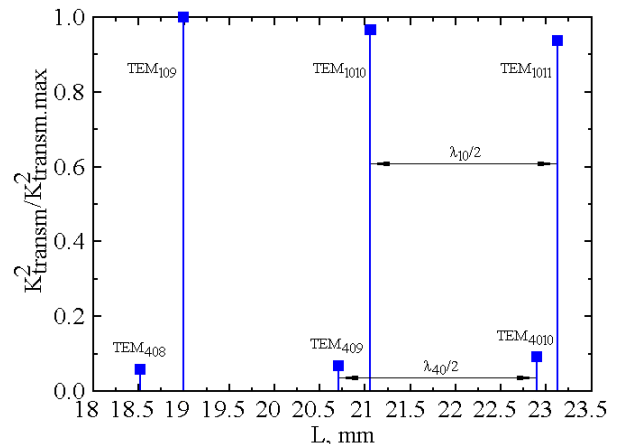


FIGURE 8. Part of the OR spectrum excited by two aperture coupling elements.

To do this, it is necessary to calculate the radius of the field spot w_0 of the TEM₀₀₁₁ oscillation on a flat mirror OR having the geometrical dimensions indicated above. As shown in work [1], for given λ and L/R $w_0=4.953$ mm. Using (2), we find that $\eta=0.815$. Thus, the excitation loss of the TEM₁₀₁₁ mode is about 18%. Therefore, in the OR, along with the TEM_{10q} mode, another higher axially asymmetric TEM_{40q} mode is excited.

It is of practical interest to compare the reduced section of the OR oscillation spectrum (Fig. 8) with the section of the oscillation spectrum of the same resonator excited by two

slot coupling elements [1]. The measurement results are shown in Fig. 9.

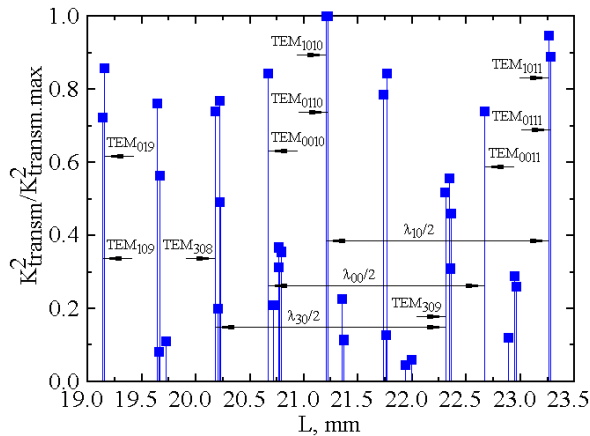


FIGURE 9. Part of the spectrum of the OR excited by two slotted coupling elements.

As the figure shows, the spectrum of oscillations in the specified resonator tuning range is dense. This is due to the inconsistent excitation of the modes in the OR with the help of slot coupling elements. In some cases, a metal screen must be put on the resonator. And this will lead to an even greater thickening of the oscillation's spectrum. Therefore, the aperture method of excitation of the modes in the OR is the most promising for adding the powers of individual sources.

The studies carried out on measuring the resonant transmission coefficient of the OR, in which the first highest axially asymmetric TEM_{10q} mode is excited, allow us to draw an important practical conclusion. When the resonator is excited with the help of two aperture coupling elements 18 (Fig. 1), which are connected in turn to the arms III and II of E -tee waveguide 13 (Fig. 1, [1]), $K_{transm}^{(III)}$ (Fig. 4÷6, curve 2) is always bigger than $K_{transm}^{(II)}$ (Fig. 4÷6, curve 3). Moreover, the greater the transmission coefficient through a one-dimensional E -polarized diffraction grating, the greater the difference in the values of the resonant transmission coefficients for each value of L/R . This is demonstrated for the TEM_{107} mode. The $K_{transm}^{(III)}$ and $K_{transm}^{(II)}$ behavior can be explained as follows. When the resonator is excited by an aperture coupling element connected to arm III of the E -tee waveguide, a slotted coupling element 24 located on spherical mirror 22 opposite this coupling element is loaded on a short-circuiting piston. Therefore, there is no additional power loss. When the OR is excited through the aperture coupling element connected to arm II of the E -tee waveguide, slot coupling element 24, located on spherical mirror 22 opposite this aperture coupling element, is loaded on the receiving path (Fig. 1). Therefore, there are additional losses associated with the ingress of part of the power, which goes to excitation TEM_{10q} mode in the resonator, into the receiving path. The greater the transmission coefficient through a one-dimensional grating, the greater the power losses. Therefore, dependencies $K_{transm}^{(II)}$ and $K_{transm}^{(III)}$ on L/R behave the same way. And since the power summation factor in the OR is determined by the formula $K_{summ}^2 = [K_{transm}^{(I)}]^2 / [K_{transm}^{(II)2} + K_{transm}^{(III)2}]$,

then such additional power losses during excitation of the resonator lead to a decrease in K_{summ}^2 . Therefore, to sum up the powers of individual sources in the OR, it is advisable to use modes with three or more field spots on the mirrors. When using the TEM_{20q} mode, signals from two separate sources enter the resonator through lateral field spots with the help of aperture coupling elements. The total signal is output from the OR using a coupling element made in the center of the third central spot of the field.

IV. CONCLUSION

The experimental studies carried out in the work allow us to draw several important practical conclusions.

1. The maximum power summation factor of two sources in an OR with aperture coupling elements is 0.9. In this case, the period of a one-dimensional diffraction grating in the openings of the coupling elements is 0.6 mm. At the same time, the maximum powers summation factor of the two sources in the resonator with the slotted excitation method is 0.72. Thus, for a more efficient powers summation of the sources taken out of the resonant volume, it is necessary to use the aperture method of excitation of the working mode in the OR.
2. The aperture method of oscillations in the resonator provides the angular selection of the spectrum in contrast to the slot method of excitation. This is due to low excitation losses, which do not exceed 13% for optimal geometric dimensions of the aperture coupling elements. This is of great practical importance when summing up the powers of individual sources in the OR. On the other hand, a rare oscillation spectrum allows the use of resonators in metal shells. This is especially important when working with high power levels, such as building microwave pulse compressors.
3. To sum up the powers of sources from the resonant volume, it is advisable to use higher axially asymmetric types of OR oscillations, for example, TEM_{10q} . However, in this case, additional losses arise when the powers are added to the resonator. They are associated with the ingress of part of the power entering the resonant volume into the receiving path. The reason is that the receiving coupling element on one mirror is located opposite the excitation of the working mode in the resonator of the aperture coupling element made on the other mirror. Therefore, when powers are added to the two sources in the resonator, instead of the TEM_{10q} mode, it is necessary to use the TEM_{20q} mode, which is already characterized by three field spots on the resonator mirrors. Signals from two sources enter the resonator through the coupling elements made in the fields' side spots. The total signal is output from the resonator through a coupling element made in the central spot of the field of the TEM_{20q} mode on the opposite mirror.

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