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Abstract

Full Text

DIFFRACTION LOSSES AND RESONANT TYPES OF OSCILLATIONS IN OPEN RESONATORS WITH CYLINDRICAL MIRRORS

V. Ya. Balakhanov, V. K. Zhivotov, A. R. Striganov

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At the present time considerable attention is being devoted to the study of the properties of open resonators with various types of reflectors. Interest in this problem is connected with the use of such resonators in quantum generators, and also with their application to the study of dielectrics and to plasma diagnostics. The objective of the present work was an experimental investigation, in the microwave region of the spectrum, of the properties of open resonators with cylindrical mirrors of the type of a multibeam Fabry–Perot radio interferometer.

The operation of the instrument mentioned above may be considered on the basis of the method of Fox and Li ⁽¹⁾, who used it to calculate a scalar expression of Huygens' principle. They obtained numerical solutions of the integral equation for a number of cases of curved mirrors. It is easy to show that the integral equation in the case of an interferometer consisting of two cylindrical mirrors splits into two equations: the first characterizes an interferometer with cylindrical mirrors in the form of infinite strips, the second an interferometer with plane mirrors in the form of infinite strips. By synthesizing the results of solving these equations, one can obtain theoretical curves for diffraction losses. The solution of the equation for plane mirrors in the form of infinite strips is given in ⁽¹⁾. The consideration of diffraction losses for infinitely long cylindrical mirrors is set forth in ^(2,3).

Recently L. A. Vainshtein ⁽⁴⁾ carried out a detailed theoretical analysis of an open resonator with cylindrical mirrors. On the basis of the solution of Maxwell's equations under certain boundary conditions, he considered the diffraction losses and resonant types of oscillations. For small diffraction losses an analytic expression was obtained for the resonant types of oscillations in the interferometer, which may be written in the form

$$\frac{2h}{\lambda} = k + (2m + 1) \frac{1}{\pi} \arcsin \sqrt{\frac{h}{2R}} + \frac{\pi}{2} (n + 1)^2 \frac{(M + \beta)^2 - \beta^2}{[(M + \beta)^2 + \beta^2]}. \quad (1)$$

Here $M = 2\sqrt{2\pi N}$, where $N = D^2/4h\lambda$ is the Fresnel number; D is the diameter of the interferometer mirrors; λ is the operating wavelength; h is the distance between the mirrors; $\beta = 0.824$; R is the radius of curvature of the

Fig. 1.

Figure 1: Fig. 1.

mirrors; k is the interference order, and the numbers m and n , taking a series of values $0, 1, 2, \dots$, characterize the secondary resonant types of oscillations of the interferometer. In relation (1) the second term on the right-hand side of the equality expresses the phase shift caused by the curvature of the mirrors; the third term is due to the finiteness of the cylindrical mirrors and is equivalent to a phase shift in an interferometer with plane mirrors having the form of infinite strips.

We attempted to realize experimentally an open resonator with cylindrical mirrors. For this purpose an apparatus was assembled consisting of a Fabry–Perot interferometer, a millimeter-wave generator, and a radiation receiver. The electromagnetic wave with $\lambda = 8$ mm generated by a klystron was transformed by a polystyrene lens and a horn into a plane wave, which excited the resonator. Upon multiple reflection of the electromagnetic wave from the mirrors, interference occurs, as a result of which, at a definite distance between the mirrors, one of the normal types of oscillations is established. The wave that passed through the resonator was directed by another polystyrene lens and horn onto the detector. The signal obtained entered an amplifier and then was regi-

was adjusted with a dial indicator. Mica plates 50μ thick served as substrates for the mirrors; a silver film $25 \text{ m}\mu$ thick was deposited on them by evaporation in vacuum. To ensure transmission of the mirrors, transparent strokes were cut in the reflecting layer. A cylindrical shape was imparted to the reflecting surfaces by special mounts. The mirror diameter was 80 mm. The mirrors were mounted on a rail by means of riders, one mirror being movable by a micrometer screw over a range of 50 mm. The position of the movable mirror relative to the fixed one was read with an accuracy of 0.01 mm.

Different types of oscillations were recorded by displacing one of the mirrors of the interferometer, and the value of the quality factor was determined from the formula

$$Q = \frac{h}{\delta h}, \quad (2)$$

where δh is the width of the maximum of the transmission band. It should be noted that, according to equation (1), for large quality factors and for small m and n , the equality $h/\delta h = \lambda/\delta\lambda$ is preserved within the experimental error. Here $\delta\lambda$ is the width of the resonator transmission band. For example, in the confocal case for mirrors with a radius of curvature of 202 mm and $\lambda = 8$ mm, the value of the quality factor determined from formula (2) differs from the value determined with the aid of the wavelength and the width of the transmission band by no more than 1%.

Fig. 2

Figure 2: Fig. 2

Fig. 1.

Figure 1 gives curves expressing the theoretical dependence of the diffraction losses for resonators with cylindrical mirrors on the Fresnel number N for mirrors with radii of curvature $R = 202$ mm and $R = 334$ mm. The curves were constructed from calculated data obtained on the basis of works ⁽¹⁻³⁾. The solid line corresponds to exact calculations; the dashed curve was constructed by the approximate calculation of Boyd and Gordon. The experimental data on the diffraction losses in the interferometer are presented in the same figure as points (triangles for mirrors with $R = 202$ mm; circles for mirrors with $R = 334$ mm). The diffraction losses were determined from the formula $\alpha'_d = k\pi/Q_k - \alpha_r$, which includes the quality factor in the k -th order, $Q_k = h/\delta h$, and the reflection losses $\alpha_r = 1 - r$. For the mirrors used, the reflection coefficient was $r = 0.915$. The scatter of the experimental points is explained by the inaccurate adjustment of the mirrors and by the influence of the mounts.

From the data obtained it is seen that the diffraction losses for resonators with cylindrical mirrors at $N > 1$ are almost completely described by the integral equation for plane mirrors in the form of infinite strips; the curvature of the mirrors has only a slight effect. The diffraction losses in this case are approximately half the losses in an interferometer with plane mirrors. At $N < 1$, the diffraction losses already depend appreciably on the radius of curvature of the mirrors. In the confocal case the diffraction losses for mirrors with $R = 202$ mm ($N = 1$) reach 8%, and for mirrors with $R = 334$ mm ($N = 0.6$) 16%. Here too the diffraction losses are approximately half the losses of a plane interferometer. If the centers of curvature of the cylindrical reflectors are made to coincide, then the diffraction losses for mirrors with $R = 202$ mm ($N = 0.5$) are 36%, while for mirrors with $R = 334$ mm ($N = 0.3$) they reach 60%. In accordance with theory ^(3,4), they are equal to the diffraction losses of an interferometer with plane mirrors.

In the confocal case, the electromagnetic field inside the interferometer has the greatest concentration at the focus of the system. The radius of the "spot" in the focal plane is determined by the relation $\rho = \sqrt{h\lambda/2\pi}$. The dimensions of the "spot" were estimated with the aid of metallic diaphragms placed in the focal plane. It turned out that, for mirrors with R equal to 80, 202, and 334 mm, the radii of the "spots" are respectively 11, 19, and 23 mm, which is in good agreement with the formula given above.

Figure 2 shows the spectrum of resonant types of oscillations obtained with a confocal interferometer with cylindrical mirrors whose radius was 80 mm and whose reflection coefficient was 0.997.

Fig. 2

The fundamental type of oscillation has the greatest intensity, and the transmission for it, upon excitation by a plane electromagnetic wave, reached 20%. Higher orders are located in the direction of increasing distance between the mirrors and have a much lower intensity (by approximately a factor of 20-50). It was found experimentally that different types of excitation of the resonator (by a plane or a non-plane wave) lead to different distributions of intensity over the normal types of oscillations. By exciting the resonators with a converging electromagnetic wave (cylindrical lenses were used for this purpose), the transmission of the fundamental type of oscillation can be increased to 50%. It should be noted that the oscillation of type TEM₁₁ is located approximately midway between the fundamental oscillations of neighboring orders. As the distance between the mirrors increases, the spectrum of resonant types of oscillations changes, and the transmission for different oscillations changes substantially.

Table 1

$\frac{N =}{D^2}$ $\frac{4h\lambda}{4h\lambda}$	$h,$ mm	Oscillation $\Delta h,$		$\Delta h,$ mm, meas.	$\frac{N =}{D^2}$ $\frac{4h\lambda}{4h\lambda}$	$h,$ mm	Oscillation $\Delta h,$		$\Delta h,$ mm, meas.
		types TEM _{mn}	mm, calc.				types TEM _{mn}	mm, calc.	
2.9	69	01	0.21	0.21	2.6	77	10	2.00	2.07
2.9	69	10	1.83	1.77	2.6	77	11	2.22	2.18
2.9	69	11	2.06	1.96	2.6	77	20	4.06	4.11
2.9	69	20	3.79	3.80	2.6	77	21	4.28	4.28
2.9	69	21	3.97	3.92	2.6	77	22	4.63	4.57
2.9	69	22	4.31	4.37	2.5	81	10	2.06	2.08
					2.5	81	11	2.30	2.30

Table 1 gives calculated data for Δh corresponding to the distance between the fundamental oscillation of type TEM₀₀ and the higher-order oscillations TEM_{mn}. The calculation formula was obtained from relation (1); moreover, in the calculations it was assumed that the distance between resonant types of oscillations is small in comparison with the distance between the mirrors of the interferometer. The same table gives the experimental values of Δh . On the basis of the results obtained, one may conclude that the pattern of the electromagnetic fields excited in an interferometer with cylindrical mirrors agrees well with theory.

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