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HCN laser with an adaptive output mirror

Yu.E. Kamenev, S.A. Masalov, A.A. Filimonova

***Abstract*.** **A device for optimal coupling between a laser resonator and the external medium, having the form of one-dimensional wire grating conjugated with a plane mirror with an aperture, is proposed, developed and tested experimentally. The dependences of the output laser power on the separation between the grating and the mirror, diameter of the aperture in the plane mirror, and the grating period, are studied. The obtained results not only confirm the possibility of using such a coupling device, but also point towards the ways and principles of its application.**

Keywords: *HCN laser, electrodynamic parameters, one-dimensional wire grating, polarisation, phase shift.*

1. Introduction

Earlier, a plane mirror with an aperture [1] or a semi-transparent anisotropic mirror in the form of a one-dimensional wire grating (OWG) [2] were used, as a rule, as the output mirror of submillimetre lasers.

In order to obtain the variable coupling between a laser resonator and the external medium, an output device was used in the form of an interference filter containing two parallel two-dimensional gratings arranged in such a way that the distance between them could be varied [3]. Such an output device is complicated to fabricate and operate, and it does not allow a variation in the output beam diameter.

At present, OWG output mirrors are widely used in submillimetre lasers. However, the maximum output power can be extracted from a laser only by using an OWG with certain electrodynamic parameters for a specific laser resonator. Moreover, it is often required to match the output laser beam diameter with the diameter of the waveguide channel. For example, the diameter of the HCN laser beam is no less than 40 mm, while the diameter of the quasi-optical waveguide channel is 20 mm [4]. Their matching requires the use of the known quasi-optical junctions, but they are difficult to make and have considerable linear dimensions [5].

Yu.E. Kamenev, S.A. Masalov, A.A. Filimonova A.Ya. Usikov Institute of Radiophysics and Electronics, National Academy of Sciences of Ukraine, ul. akad. Proskury 12, 61085 Kharkov, Ukraine;
e-mail: kamenev@ire.kharkov.ua, masalov@ire.kharkov.ua

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The aim of this paper is to study the possibility of using a hybrid mirror adapted to the external waveguide channels.

2. Experimental

It is known that when linearly polarised electromagnetic radiation with polarisation parallel to the grating wires and a wavelength much longer than the grating period is incident on an OWG, a part of this radiation passes through the OWG, while the other part is reflected from the grating. The transmitted signal acquires a phase shift relative to the incident radiation and as if 'falls through' the grating, i.e., is accelerated by it. Depending on the structural parameters of the OWG, the phase shift may be considerable [6].

In [7, 8], a 337-μm HCN laser was used to determine experimentally the phase shift for various OWGs. The studies revealed a good agreement between the theoretical [6] and experimental results. Their analysis made it possible to propose the design of a device for coupling between a laser resonator and the external medium, which allows not only an optimisation of the coupling but also a control over the output beam diameter.

The proposed device contains two plane – parallel mirrors separated from each other, the inner one in the form of an OWG and the outer one in the form of a plane mirror with an aperture. The separation between the mirrors is

$$L = \frac{n\lambda}{2} + \Delta L, \qquad (1)$$

where $n = 0, 1, 2, 3, \ldots$; and ΔL:, corresponds to the phase shift introduced by the OWG. Physically, this means that the plane mirror with an aperture is located at the node of a standing wave produced by the OWG.

The proposed output device was tested with the help of a modernised electric-discharge HCN laser (Fig. 1) [9]. The laser radiation power was measured experimentally for various coupling devices. Initially, the dependence of the laser radiation power W on the aperture diameter D in the output mirrors was measured [without grating (*3*)], which were subsequently used together with the OWG. A typical dependence $W(D)$ presented in Fig. 2 shows that the optimal aperture diameter for the given laser resonator is $\sim$6 mm, while the maximum diameter at which the radiation is produced is 12 mm.

In the next stage, the investigated OWG and a mirror with an aperture of diameter 7 or 8 mm were installed and the optimal value of L was determined experimentally. The

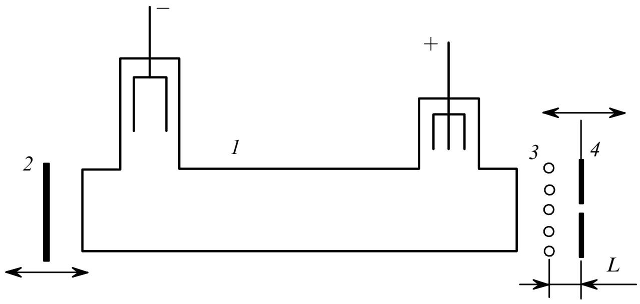

Figure 1. Schematic of a laser emitter: (*1*) discharge tube; (*2*) highly reflecting mirror; (*3*) OWG; (*4*) plane mirror with an aperture.

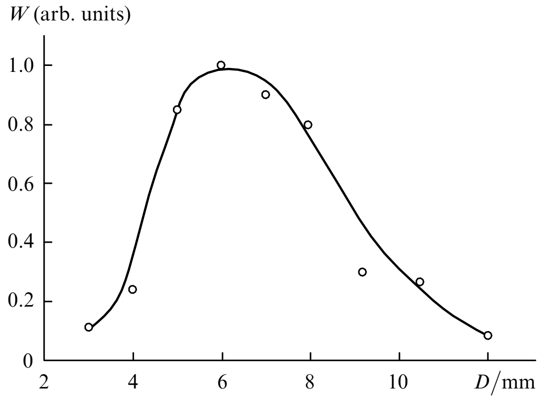

Figure 2. Dependence of the laser radiation power W on the diameter D of the aperture in a plane mirror.

dependence of the laser power on the diameter of the aperture was then measured for this value of L. The separation L was chosen with the help of a set of 15-μm-thick rings or a special adjusting unit in which the OWG and the plane mirror with an aperture were aligned separately. Initially, the OWG and the plane mirror in the adjusting unit were separated by a distance of 29.5 mm from each other and the mirror could be displaced parallel to the OWG. The gratings used in this work were 3-mm-thick kovar rings with an inner diameter of 40 mm and an outer diameter of 50 mm, to which tungsten wires were fastened.

The phase shift and transmission coefficient for these gratings for normally incident electromagnetic waves we estimated from the approximate analytic expressions [6]

$$T_E = 1 - \left[\frac{1}{1+2i\chi\ln(\pi S)} + \frac{2iQ}{1+iQ}\left(1 - \frac{\pi^2 S^2}{12}\right)\right] = |T_E|\exp(i\arg T_E), \qquad (2)$$

and

$$T_H = 1 - iQ\left[\frac{1}{1+Q} - \frac{2}{(1-iQ)^2}\left(1 + \frac{\pi^2 S^2}{12}\right)\right] = |T_H|\exp(i\arg T_H), \qquad (3)$$

where T_E and T_H are the complex transmission coefficients for components with E and H polarisations, respectively; $Q = \pi^2 S^2/4$; $S = d/l$; $\chi = l/\lambda$; d is the wire diameter in micrometers; and l is the grating period (in micrometers). These formulas can be used to determine the absolute values (transmission coefficients) and arguments (phase shifts) of T_E and T_H. Table 1 contains the results of calculations for several types of gratings.

Note that gratings with a period of 50 and 60 μm have the transmission coefficient $|T_E|$ lower than the gain in the active medium in the HCN laser, while for gratings with a period of 100 and 200 μm, the transmission coefficient is much higher. Thus, the first two gratings can be used as independent output mirrors. The phase shift φ_E (see Table 1) determines the theoretical distance of ΔL.

3. Experimental results and discussion

Figure 3 shows the dependence of the output laser power on the aperture diameter in a plane mirror. The coupling device contains a mirror with an aperture and an OWG with a period of 50 μm, the aperture being partially covered by wire. One can see from this dependence that the radiation power increases monotonically with increasing the aperture diameter.

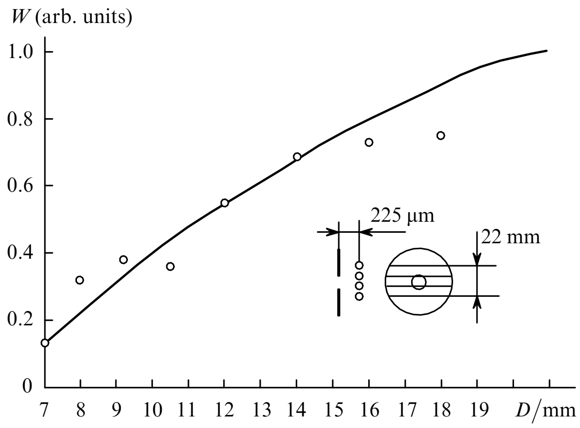

Figure 3. Dependence of the laser radiation power W on the diameter D of the aperture in a plane mirror (the OWG parameters are $l = 50$ μm, $d = 10$ μm). The inset shows the scheme of a coupling device formed by a plane mirror with an aperture and an OWG.

Table 1.

l/μm	d/μm	S	χ	$\lvert T_E\rvert$	φ_E	$\lvert T_H\rvert$	φ_H	$\Delta\varphi = \varphi_H - \varphi_E$
50	10	0.2	0.148	0.165	−83°47′	0.99902	54′	84°41′
60	10	0.167	0.178	0.248	−78°24′	0.99932	44′	79°8′
100	10	0.1	0.297	0.578	−56°20′	0.99976	26′	56°46′
200	10	0.05	0.593	0.913	−24°54′	0.99994	13′	25°6′

Note: φ_E and φ_H are the phase shifts for waves with E and H polarisations, respectively.

For an initial separation $L = 29.5$ mm between the OWG and the plane mirror with the aperture of diameter 18 mm and upon a subsequent parallel displacement of the mirror, it was found that lasing in this configuration occured when L was varied in the range ± 15 mm and was repeated with a period of $\lambda/2$. For comparison, we measured the laser power by using for the output mirror a grating with a period of 50 μm and a wire diameter of 10 μm. The power was found to be 10 % higher than the case when a mirror with the aperture of diameter 21 mm was used in the output device (see Fig. 3).

Figure 4 shows the dependence of the laser radiation power on the aperture diameter in a plane mirror for the case when an OWG with a period of 60 μm was used. Apart from radiation at 337 μm, we also studied in this configuration radiation at 311 μm. It follows from the dependences presented in Fig. 4 that for radiation at 337 μm, a saturation of the output laser power is observed with increasing the aperture diameter. This, in turn, points to an optimal coupling, like the dependence for radiation at 311 μm. When such a grating is used (without the mirror with an aperture), the laser radiation power is 0.6 at 377 μm and 0.2 at 311 μm of the maximum power obtained by using an OWG with $l = 50$ μm and $d = 10$ μm as the output mirror.

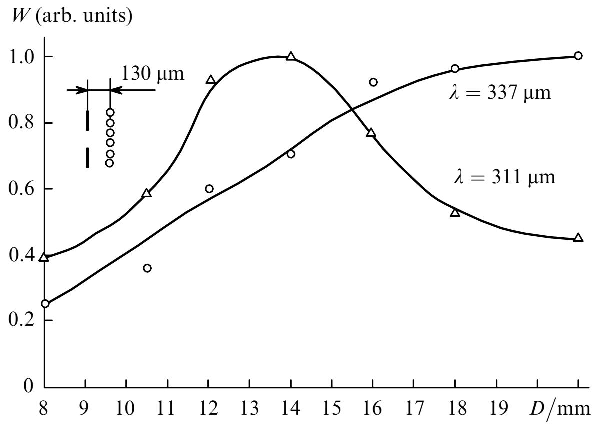

Figure 4. Dependence of the laser radiation power W on the diameter D of the aperture in a plane mirror (the OWG parameters are $l = 60$ μm, $d = 15$ μm).

Figure 5 shows the dependence of the laser radiation power at 377 μm on the change in separation between the OWG and the mirror with an aperture (the initial separation was set at 29.5 mm) for a 21-mm hole diameter in the plane mirror. One can see that the maximum output laser power is repeated with a period $\lambda/2$. Lasing occurs for any separation between a mirror with an aperture and an OWG. This is explained by the fact that the transmission coefficient of the grating is lower than the gain in the active medium.

Similar experiments were also performed with gratings with periods of 100, 200 and 300 μm. Figure 6 shows the dependence of the laser power on the diameter of the aperture in a plane mirror obtained by using an OWG with a period of 100 μm. The distance L between the OWG and the plane mirror was 100 – 130 μm. The optimal diameter of the aperture in the plane mirror for such an OWG was 10.5 mm. For aperture diameters of 12 and 14 mm, the output power was lower and lasing was unstable.

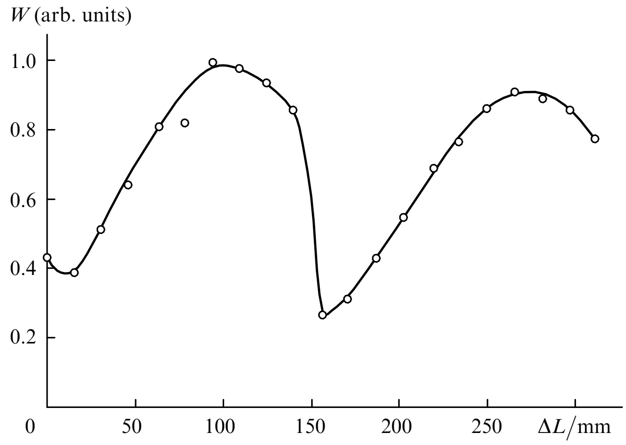

Figure 5. Dependence of the radiation power W of a 337-μm laser on the variation ΔL of the separation between a plane mirror with a 21-mm aperture and an OWG (the OWG parameters are $l = 60$ μm, $d = 15$ μm).

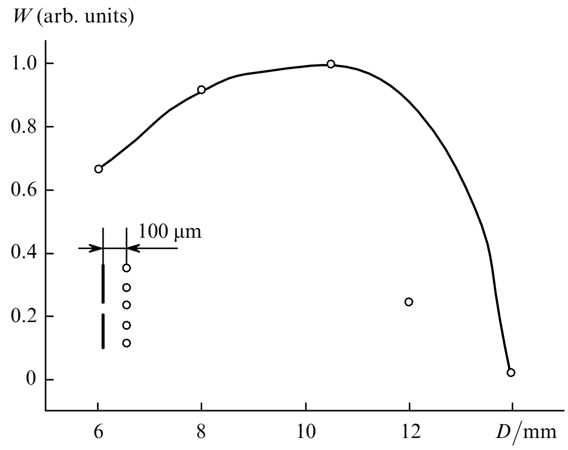

Figure 6. Dependence of the laser radiation power W on the diameter D of the aperture in a plane mirror (the OWG parameters are $l = 100$ μm, $d = 10$ μm).

No lasing was observed for an aperture diameter of 16 mm. Note that the maximum output power for such a grating was about the same as for the gratings considered above. For a grating with a period of 200 μm, a separation between the OWG and the plane mirror equal to 100 μm and an aperture of diameter up to 8 mm, laser radiation with a polarisation parallel and perpendicular to the grating wires was observed. The power of laser radiation with polarisation parallel to the grating wires was 1.5 times higher than in the case of radiation with transverse polarisation. No signal was observed for an aperture diameter of 9.5 mm.

For a grating with a period 300 μm, lasing was obtained for an aperture diameter of 8 mm and a separation of 200 μm between the mirror and the grating. The intensity of a signal with polarisation parallel to the grating wires was the same as for the transverse polarisation. Note that for $\chi > 0.5$, the effect of the OWG on the E- and H-components is comparable and may become equal for certain values of parameters χ and S [6].

Experiments were also performed for other configurations of the output device consisting of an OWG and a plane mirror with an aperture. In particular, mirrors with rectangular apertures were used, while gratings with complete or partial filling of apertures by wires were used as the OWG, the size of the aperture matching with rectangular aperture in the mirror. The measured energy parameters of laser radiation were no worse than the above parameters.

4. Conclusions

Thus, the results obtained in this work not only confirm the efficiency of the coupling device proposed here, but also indicate the practical ways of realisation of such devices as well as the limits of their applicability. The device allows a transformation of the beam diameter and an optimal coupling of the laser resonator with the external medium by varying the OWG parameters and the aperture diameter in the mirror. In addition, this device makes it possible to obtain the output beam whose diameter corresponds to that of the external waveguide channel. It can be used successfully as a junction between quasi-optical waveguides of various diameters in the millimetre and submillimetre ranges. The experimental parameters of such junctions can be slightly worse than those of the known quasi-optical junctions [5].

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