LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS

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Application of a submillimetre HCN laser for determining the electrodynamic parameters of one-dimensional wire gratings

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Abstract. **A method is proposed and a device is described for determining the electrodynamic parameters of one-dimensional wire gratings in the submillimetre range. The grating under study was used as the output mirror of the laser. The transmission coefficient and the phase shift are determined experimentally for several gratings with different parameters at a wavelength of 337 μm.**

Keywords: *HCN laser, electrodynamic parameters, one-dimensional wire grating, polarisation, flat-roof mirror.*

Due to their unique electrodynamic properties, one-dimensional wire gratings (ODWGs) can be used as transmitting or reflecting polarising elements in various devices operating in the millimetre and submillimetre wavelength ranges [1]. Results of theoretical studies of electrodynamic properties of various semitransparent (including one-dimensional wire) gratings and reflection gratings with different parameters $\chi = l/\lambda$ and $S = d/l$ (where l is the grating period, d is the wire diameter and λ is the wavelength) have been systematised in [2, 3]. Earlier, the transmission coefficient of ODWGs was determined experimentally by irradiating the grating under study and then comparing the signal transmitted through the grating with the one reflected from it [4], or by comparing the signals transmitted through the grating and not transmitted through it [5]. The phase shift was measured also by analysing radiation transmitted through the grating [6, 7].

In this work, we describe a method for determining the electrodynamic parameters of ODWGs (transmission coefficient and phase shift of the wave transmitted through the grating under the condition $\chi \ll 1$) in the submillimetre range by using a 337-μm HCN laser.

In this technique, we use the known property of a flat-roof mirror to change the azimuth angle of polarisation of the wave reflected from it by 2α, where α is the azimuth angle of polarisation of the wave incident on a 90° flat-roof mirror. Because of the polarising properties of the grating, the wave transmitted through it will contain two orthogonal linearly polarised components: the component $E^2 \sin^2 2\alpha$ with a polarisation vector perpendicular to the grating wires (it is assumed that the ODWG is completely transparent to this component), and the component $E^2|T_E| \cos^2 2\alpha$ with a polarisation vector parallel to the grating wires, where E is the amplitude of a wave incident at a right angle on the grating and $|T_E|$ is the ODWG transmission coefficient for a polarisation whose vector is parallel to the wires of the grating. Comparing these components, we arrive at the relation

$$|T_E| = \tan^2 2\alpha. \tag{1}$$

Thus, the experimental dependence of the output power of the E and H components on the angle α between the wires of the grating and the edge of a flat-roof mirror [8] gives the angle α at which the powers of these components are equal. The transmission coefficient $|T_E|$ is determined from expression (1). This technique can also be used for determining the phase shift $\Delta\varphi$ appearing between two wave components linearly polarised parallel and perpendicular to the grating wires (i.e., the E and H components) during propagation of the wave through the ODWG.

It is well known that the polarisation parameters of a wave are expressed in terms of the amplitudes of orthogonal E and H components and the phase difference between them [9], and also that upon normal incidence of a linearly polarised wave with an arbitrary azimuth angle on the ODWG, the transmitted wave will have two phase-shifted orthogonal linearly polarised components. Therefore, the output radiation will always be elliptically polarised in the general case. The phase shift is measured by determining experimentally the angle α for which two transmitted E and H components will be equal, and by measuring the azimuthal dependence of the output signal for this angle. This dependence will be elliptical in shape and (due to the equality of the components) the angles of inclination of the ellipse axes to the grating wires will be 45°. Then, the major and minor axes of the ellipse are measured, and the phase shift $\Delta\varphi$ is determined from the relation [9]

$$\Delta\varphi = \arccos \frac{A_2^2 - A_1^2}{A_2^2 + A_1^2}, \tag{2}$$

where A_1 and A_2 are the minor and major semiaxes of the ellipse, respectively.

In the experimental setup on which this technique is realised, we use an electric-discharge hollow-cathode HCN laser [10], whose resonator (Fig. 1) was formed by a glass

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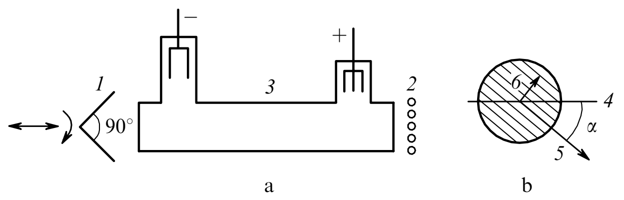

Figure 1. Scheme of the laser (a) and azimuthal arrangement of mirrors (b): (*1*) flat-roof mirror; (*2*) ODWG under study; (*3*) glass waveguide; (*4*) edge of the flat-roof mirror; (*5*) *E* component; (*6*) *H* component.

waveguide with the inner diameter 38 mm, the ODWG under study as a mirror, and a half-wave phase mirror in the form of a flat-roof mirror with an angle 90° between the faces, mounted in such a way that it could be displaced along the resonator axis and rotated about its axis.

Radiation was measured with a polarisation-insensitive pyroelectric detector and its polarisation was analysed with a rotating grating mounted at an angle to the axis of the output beam [11]. Quasioptical elements were used as the channel [1].

The angle α was varied in the experiment discretely by rotating the flat-roof mirror about its axis and by displacing this mirror along the resonator axis to attain the maximum laser radiation power for this angle. The dependence of the output laser power on the angle between the wires of the output grating and the edge of the flat-roof mirror was recorded for two components polarised parallel and perpendicular to the grating wires (a typical dependence is shown in Fig. 2).

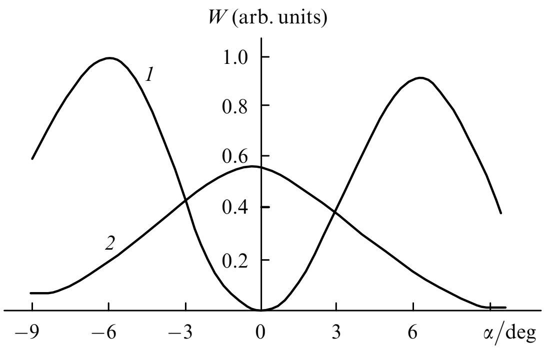

Figure 2. Dependence of laser radiation power *W* on the angle between the edge of a flat-roof mirror and wires of the output grating for (*1*) *H*-polarisation oriented orthogonally to the grating wires, and (*2*) *E*-polarisation oriented parallel to the wires. Spacing of the wire grating is 30 μm and the wire diameter is 8 μm.

By analysing these dependences, we determined the angle at which both components are equal [the point of intersection of curves (*1*) and (*2*) in Fig. 2]. This angle was then used to calculate the transmission coefficient of the ODWG from expression (1). To determine the phase shift, this angle was fixed and the azimuthal dependence of the output laser radiation, which was polarised elliptically with a 45° inclination of the ellipse relative to the grating wires, was recorded. Then, the amplitudes of the major and minor semiaxes of the ellipse were measured and the phase shift was calculated from expression (2).

Table 1.

Grating spacing/μm	Wire diameter/μm	$\lvert T_E\rvert_{\text{exp}}$	$\lvert T_E\rvert_{\text{theor}}$	$\Delta\varphi_{\text{exp}}$	$\Delta\varphi_{\text{theor}}$
30	8	0.009	0.004	87°30′	90°56′
30	15	0.002	0.0006	112°	119°43′
42	10	0.023	0.011	86°30′	88°54′

This technique for determining the electrodynamic parameters of the ODWG was verified for three gratings of tungsten wire fastened to covar rings of diameter 40 mm. The results are presented in Table 1.

The electrodynamic parameters of the ODWG were estimated using approximate analytic expressions borrowed from monographs [2, 3]. In the case of normal incidence, these expressions are

$$T_E = 1 - \left[\frac{1}{1+2\mathrm{i}\chi\ln(\pi S)} + \frac{2\mathrm{i}Q}{(1+\mathrm{i}Q)}\left(1-\frac{\pi^2 S^2}{12}\right)\right]$$
$$= |T_E|\exp(\mathrm{i}\arg T_E), \tag{3}$$

$$T_H = 1 - \mathrm{i}Q\left[\frac{1}{1+\mathrm{i}Q} - \frac{2}{(1-\mathrm{i}Q)^2}\left(1+\frac{\pi^2 S^2}{12}\right)\right]$$
$$= |T_H|\exp(\mathrm{i}\arg T_H), \tag{4}$$

where $Q = \pi^2 S^2\chi/4$; T_E and T_H are the complex transmission coefficients of the ODWG for the E and H components, respectively. Expressions (3) and (4) can be used to determine the modulus (transmission coefficient) and argument (phase shift) of complex transmission coefficients with an error 1 % for $\chi < 0.5$ and $S < 0.5$. In this case, $\Delta\varphi = \arg T_E - \arg T_H$.

Although no attempts were made in the experiments to increase the accuracy of the experimental data and the measuring error was not estimated, a good agreement between the experimental and theoretical results was obtained, especially the results concerning the phase shift. The discrepancy between theoretical and experimental results for the transmission coefficient is mainly due to the error in determining the angle α, grating imperfection, etc. Hence, while using the technique described above for determining the ODWG parameters precisely or for verifying the correctness of the theoretical approach, it is necessary to estimate first the error of the method, and carry out multiple measurements followed by averaging of the results.

In conclusion, note that the practical significance of the approach used by us lies in its applicability for determining the electrodynamic parameters of ODWGs with $\chi < 0.2$ and $S < 0.5$ for wires of any shape.

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