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An HCN laser with a two-layer anisotropic output mirror

S.A. Andrenko, Yu.E. Kamenev, V.L. Pazynin

***Abstract*. A device for coupling a laser resonator with the external medium consisting of two identical one-dimensional wire gratings positioned in parallel planes with a mutual shift of wires in these planes by half the period is proposed, developed, and experimentally studied. The possibility of using this structure is proven theoretically. The scheme of a laser source used to study the dependence of the output laser power on the distance between the gratings is presented. It is experimentally found that the transmittance of the proposed structure strongly depends both on the distance between the grating planes and on the relative period shift of gratings in these planes.**

Keywords: *HCN laser, one-dimensional wire grating, grating period, transmission, output mirror.*

1. Introduction

The periodic structures in the form of diffraction gratings belong to the objects scattering electromagnetic waves. These structures are widely used in real devices in the optical region. At present, the theoretical study and practical application of these structures have come to a new stage related to the use of the terahertz region and to the progress in the quasi-optical technique.

The properties of gratings strongly depend on the parameter χ, which is determined by the ratio of the grating period l to the wavelength λ of the electromagnetic radiation interacting with the grating, $\chi = l/\lambda$. By convention such interactions are divided into three types: long-wavelength ($\chi \ll 1$), short-wavelength ($\chi \gg 1$) and resonance ($\chi \sim 1$). The methods and conditions for analysing the occurring phenomena are chosen based on the values of χ. The basic work on this subject [1] stimulated the development of the electrodynamic theory of periodic gratings. The authors of subsequent monographs [2, 3] presented the methods and algorithms for theoretical investigation of various periodic structures and analysed their properties.

S.A. Andrenko, Yu.E. Kamenev, V.L. Pazynin A.Ya. Usikov Institute of Radiophysics and Electronics, National Academy of Sciences of Ukraine, ul. Acad. Proskury 12, 61085 Kharkov, Ukraine;
e-mail: kamenev@ire.kharkov.ua

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A key object in the development of terahertz quasi-optical elements is a periodic structure made in the form of a one-dimensional wire grating (OWG). This OWG was used to design quasi-optical devices similar to waveguide devices operating at shorter wavelengths [4]. The use of OWGs in terahertz lasers allowed one to create HCN lasers with specific intensity distributions of the output radiation [5], to optimise coupling between a laser and the external medium [6], to control the polarisation-frequency characteristics of the output radiation [7 – 9], to control the beam diameter [10], and to optimise the interaction of an active medium with electromagnetic radiation [11]. The use of special laser resonance systems and specific laser operation regimes makes it possible to determine the parameters of OWGs serving as output laser mirrors [12]. The OWGs used in HCN lasers previously had to satisfy the condition $\chi \ll 1$ and have a transmittance no higher than 0.06 for linearly polarised radiation whose electric vector was parallel to the grating wires.

The aim of this study is to optimise the coupling between a laser resonator and the external medium using as an output mirror a structure consisting of two identical adjacent OWGs, whose parameter χ can be close to unity.

2. Theoretical background and experimental technique

To use a two-layer OWG as a laser output mirror, it is necessary to know the transmission coefficient of this structure. The transmission coefficients were calculated by the finite-difference time-domain (FDTD) method [13]. This method is universal, simple in use, and allows one to simulate electrodynamic structures of different types (in our case, infinite OWGs) under the condition that the space restric-tion problem is solved correctly. In this work, we used the exact boundary conditions given in [14].

For the Floquet channel, we formulated the initial boundary problem [14] for the electric field component parallel to the metal wires of the grating. Discretisation of this problem in combination with 'absorbing' boundary conditions [14] followed by solution of this problem within a standard FDTD scheme allowed us to obtain correct results with an accuracy limited only by the error in the difference scheme. Using the standard Fourier transform, these results (OWG transmission coefficients) were transformed from the time to frequency domain. The dependences shown in Fig. 1 were found choosing a frequency of 0.89 THz (λ = 337 μm) from the obtained frequency spectrum. The calculations were performed for OWGs with the wire diameter d = 10 μm and

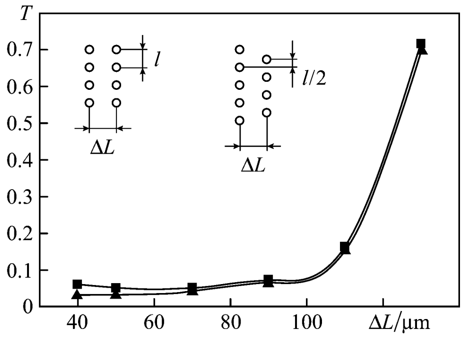

Figure 1. Theoretical dependences of the transmission coefficient T of the output structure on the distance ΔL between the gratings for the zero (■) and half-period (▲) mutual shifts of OWG wires (see the inset).

the grating period $l = 100$ μm, which corresponds to $\chi \approx 0.3$. From Fig. 1 one can see that there exists a range of intergrating distances ΔL in which the transmission coefficient of the considered structure is ~ 0.05, which indicates that it can be used as an output mirror of an HCN laser.

In [12], the authors used an OWG as a laser output mirror and measured its transmission coefficient for the normally incident electromagnetic radiation with $\lambda = 337$ μm, as well as the phase shift of this radiation. The obtained results made it possible to develop and study an HCN laser with an output device consisting of two mirrors, one of which was a one-dimensional wire grating and the second was a plane mirror with an aperture [9]. Experimental studies not only proved the functionality of this scheme but also suggested fields of its application. The main advantage of the proposed device is the possibility of obtaining an output beam with a diameter corresponding to the diameter of the external waveguide channel.

In this work, we study an HCN laser with an output mirror consisting of two identical OWGs with the period $l = 100$ μm and the wire diameter $d = 10$ μm. At first, the gratings were placed at the distance $\Delta L \sim 60$ μm from each other, which approximately corresponded to the theoretical phase shift of an electromagnetic wave passed through this grating [10], and the wires of these gratings were shifted from each other by half the period.

The laser scheme is shown in Fig. 2. The laser medium was excited by a HF generator at a frequency of 13.5 MHz using cylindrical electrodes positioned outside a thin-wall glass discharge tube. The HF generator power was ~ 500 W.

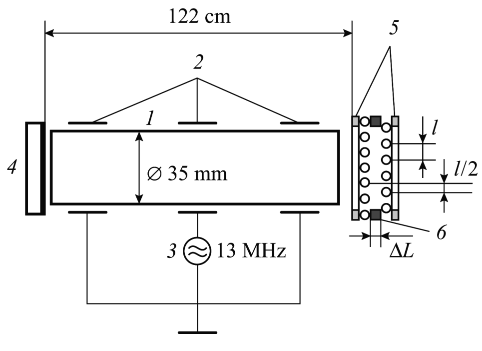

Figure 2. Laser scheme: (*1*) discharge tube; (*2*) HF electrodes, (*3*) HF generator, (*4*) highly reflecting mirror; (*5*) OWGs; (*6*) spacer.

We used standard OWGs – kovar rings with an inner diameter of 40 mm, an outer diameter of 50 mm, and a thickness of 3 mm, to which tungsten wires 10 μm in diameter were fastened with a period of 100 μm. The distance between the gratings was fixed with the help of a ring spacer (*6*); the relative position of the wires was controlled with a microscope.

3. Experimental results and analysis

We experimentally studied the dependence of the output power W on the distance ΔL between the gratings when the mutual shift of OWG wires was exactly half the period (Fig. 3). One can see that the laser radiation power reaches a maximum when the distance between the gratings is ~ 100 μm. It is found that lasing occurs in the region of $\Delta L = 60-160$ μm. Our experiments showed that, at $\Delta L \approx 60$ and 160 μm, lasing is unstable and the laser cavity requires fine alignment. No lasing was observed at $\Delta L < 60$ μm; at $\Delta L > 160$ μm, within our experimental capabilities, we observed no lasing at $\Delta L = 180$ and 190 μm and recorded a stable lasing at $\Delta L = 235$ μm, which proves that this device can operate at ΔL divisible by $\lambda/2$. The experiments on determination of the accuracy required for the mutual shift of the grating wires showed that, at $\Delta L = 100$ μm, lasing occurred even in the absence of shift, while, as ΔL approached 60 and 160 μm, the half-period shift between the wires of two OWGs must be more accurate. It should be noted that the OWG wires must be strictly parallel in all the experiments.

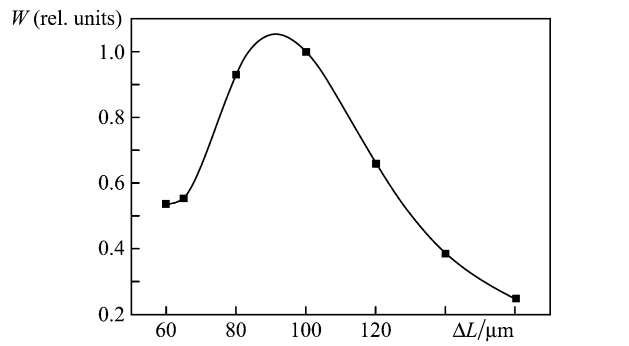

Figure 3. Dependence of the output laser power on the distance between gratings for the mutual shift of OWG wires by half the period.

Note for comparison that the maximum laser power obtained when using an output mirror consisting of one OWG with the period $l = 60$ μm and the wire diameter $d = 15$ μm comprised 0.9 of the power obtained using two OWGs ($l = 100$ μm, $d = 10$ μm) with $\Delta L = 100$ μm, which points to the nonoptimal coupling coefficient of the OWG with $l = 60$ μm and $d = 15$ μm.

We performed qualitative experiments to determine the transmittance of double OWGs as a function of the mutual shift of their wires. We used linearly polarised radiation with $\lambda = 337$ μm. Figure 4 shows the experimental dependences of the transmission coefficients of double OWGs on ΔL in the case of unshifted and half-period shifted wires. One can see that, at ΔL close to 100 μm, the transmission coefficient does not depend on the mutual shift of OWG wires.

Analysing the results, we should note that the theoretical basis for using the described structure as an output laser mirror is the existence of a region where the transmission coefficient is ~ 0.05. Figure 1 shows that this region corresponds to the distance between gratings $\Delta L = 40-100$ μm. The maximum output power was recorded at $\Delta L \sim 90$ μm (Fig. 3). Comparison of the dependences presented in Figs 1 and 4 shows that the theoretical and experimental results coincide in the region of $\Delta L = 60-100$ μm. At $\Delta L > 100$ μm, the theoretical transmission coefficient increases (Fig. 1), while the experimental transmission coefficient only tends to increase (Fig. 4). The study of the difference between the theoretical and experimental transmission coefficients at $\Delta L < 60$ μm requires special experiments and theoretical calculations, which is beyond the scope of this paper and will be the subject of further investigations.

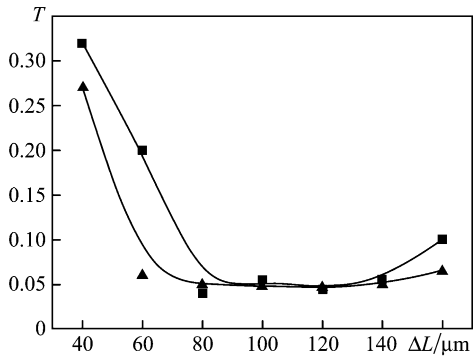

Figure 4. Experimental dependences of the transmission coefficient of the output structure on the distance between the gratings for the zero (■) and half-period (▲) mutual shifts of OWG wires.

4. Conclusions

The experimental results obtained in this work correlate with previous calculations. The used theory of multilayer structures can be tested and refined with the help of the described experimental technique in further investigations. Using a multilayer structure as an output laser mirror, one can rather accurately measure its transmittance as a function of the mutual shift of wires or as a function of the distance between the OWGs. The practical importance of the obtained results consists in the possibility of using more widely spaced OWGs ($\chi \sim 1$) as output laser mirrors. This is especially important for lasers operating at shorter wavelengths than HCN lasers (for example, H_2O and DCN lasers), because the fabrication of OWGs for these lasers runs into technological problems. The application of such a structure makes it possible to change and optimise the coupling of a laser with the external medium, which can be used to determine the parameters of the active laser medium. This structure controls the polarisation of the output laser radiation and does not affect the intensity distribution in the laser beam.

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