

# Sectional Circular Gradient Grating with Improved Focusing Characteristics in THz Frequency Range

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**Abstract**—A method for increasing the focusing properties of annular gradient gratings is presented in this work. The interaction of the coherent radiation of the terahertz range with gradient gratings consisting of concentric metal rings is investigated. The thickness and width of the metal rings is much less than the radiation wavelength. The distance between the rings varies in the radial direction, but does not exceed half the wavelength. It was previously found that such planar structures have focusing properties. Moreover, they can simultaneously serve as a concave mirror and a focusing lens. The combination of these properties is promising for laser output mirrors. This makes it possible to reduce diffraction losses in the laser cavity and improve the spatial and angular characteristics of the laser beam. In addition, laser radiation acquires azimuthal polarization, which has certain advantages. In some cases, an increase in the focusing properties of gradient gratings is required. A significant increase in focusing properties can be achieved by sectioning according to the principle of Fresnel lenses. However, phase inhomogeneities arise at the boundaries of the sections. This disrupts focus and introduces additional loss. In the work, a method for increasing the focusing properties of sectioned circular gradient gratings by giving them a stepped shape is considered. The results of modeling such gratings are presented.

**Keywords**—gradient circular grating; phase step; terahertz range; focusing properties.

## I. INTRODUCTION

Periodic structures are used in various frequency ranges. It is no exception and terahertz (THz) range. In this range it is not difficult to perform a period of the structure significantly less than the wavelength. In their manufacture, you can use the photolithography method or other technologies used in microelectronics. Metal periodic structures (grating) located on transparent dielectric substrates are widely used. Such gratings can be used as partially transparent mirrors in THz lasers.

Periodic structures have a wide variety of geometric configurations. This allows to change their physical properties over a wide range [1]. The transmission and reflection coefficients of the gratings can be widely controlled by changing the ratio between metallized and transparent sections. In this case the phase shift of the reflected and transmitted through the lattice electromagnetic waves can also change. Gratings, which are used as output mirrors of

lasers, make it possible to obtain a specified polarization of the laser beam. For example, structures consisting of concentric rings make it possible to obtain laser radiation with azimuthal polarization [2]. At azimuthal polarization, the electric field vector is oriented perpendicular to the beam radius. Consequently, the central symmetry of the orientation of the electric field vector along the beam cross section is observed. Such beams can be focused in a region close to a point or to a segment parallel to the direction of the beam. Such focusing is especially in demand in the infrared range during laser processing of materials. In the THz range, such properties are also useful, for example, at a concentration of radiation at a point detector.

Periodic structures may also have focusing abilities. A striking example of this are gradient gratings – periodic structures with inhomogeneous parameters [3–12]. A wide variety of such structures has already been proposed and developed. Structures with axial symmetry are the most functional. Gradient circular gratings consisting of concentric metal rings have been proposed. In such gratings, the distance between the rings increases in the radial direction, which makes it possible to focus the reflected and transmitted radiation through them [13]. Therefore, such gratings combine the properties of a concave mirror and a focusing lens. The combination of such properties is in demand for use as output mirrors of laser resonators. This makes it possible to reduce losses in the laser cavity and improve the energy characteristics of the laser beam. The advantages of such output mirrors include the fact that laser radiation acquires azimuthal polarization.

A significant advantage of annular gradient gratings is the possibility of changes in a wide range of their physical properties.. By varying the geometric parameters of gradient circular gratings a large variety of reflection and transmission coefficients can be obtained for them, as well as a wide range of their focusing and scattering properties. Reflection and transmission coefficients can be changed without significant restrictions. Minimum reflection and maximum transmission are limited by the substrate material (no metal coating). Maximum reflection is limited by the reflective properties of the metal coating.. Focusing and scattering abilities have significant limitations. In the direction of reducing the focusing or scattering properties, there are no restrictions. A complete absence of such properties can be obtained if the

grating parameters do not change in the radial direction. In the direction of increasing the focusing and scattering properties (reducing the focal length), there are significant limitations. These limitations are determined by the diameter of the lattice, the wavelength, and the maximum possible difference in phase shifts obtained by radiation when it interacts with the central part of the gradient structure and along its edges. Approximately focal length can be calculated by the formula:

$$F \approx \frac{1}{2} \times \frac{\left(\frac{d}{2}\right)^2 + \left(\frac{2\pi\lambda}{\Delta\phi}\right)^2}{2\left(\frac{2\pi\lambda}{\Delta\phi}\right)},$$

where  $d$  is the diameter of the circular gradient grating,  $\lambda$  is the radiation wavelength,  $\Delta\phi$  is the phase shift difference obtained by the wave during its interaction with the gradient grating at its center and along its edges.

Thus, the minimum focal length is limited by the maximum possible difference in phase shifts in the center and along the edges of the grating. The phase shift mainly depends on the grating fill factor. The fill factor can be changed from a solid metal surface to a complete absence of metal coating. Therefore, it is possible to obtain a half-wave phase shift as much as possible. The change in the wave front caused by the difference in phase shifts in the center and along the edges of the annular gradient grating ( $2\pi\lambda/\Delta\phi$ ) is equivalent to the concavity of a spherical mirror or the gradient of the lens thickness multiplied by the refractive index of its material. By increasing the wavelength, focusing abilities can be increased. In addition, focusing abilities increase with decreasing grating diameter. This is similar to reducing the diameter of a lens or spherical mirror. For example, a gradient grating with a diameter of 40 mm can provide a minimum focal length of about 600 mm (at a wavelength of about 4  $\mu\text{m}$ ). A grating having a diameter of 4 mm provides a minimum focal length of approximately 60 mm (at the same wavelength) [13]. Such focusing properties are entirely enough for use in real THz lasers. In THz gas discharge lasers with a cavity length of 1 m and a diameter of 40 mm, spherical mirrors with a radius of curvature of 5 to 10 m are used to compensate for the scattering properties of the gas discharge.

However, for some specific applications of gradient gratings, limiting the minimum focal length can cause problems. For example such problems arise in devices for focusing radiation on a point receiver. In the infrared range, a short focal length is required for cutting and drilling materials. To reduce the focal length, one can use the principles underlying Fresnel lenses when the focusing system is a combination of individual ring elements. For this it was proposed that the annular gradient grating be partitioned, consisting of repeating concentric groups of rings [14–17]. An example of a partitioned lattice consisting of two groups of rings is shown in Fig. 1.

The period changes smoothly in each group of rings. Such sectioning can significantly reduce the focal length of the gradient grating. However, a sharp phase change of the reflected and transmitted waves occurs at the junction of the ring groups, which leads to a violation of the smoothing of the phase front and the blurring of the focusing spot.

The goal of this work is to improve the focusing properties of circular sectioned gradient gratings.

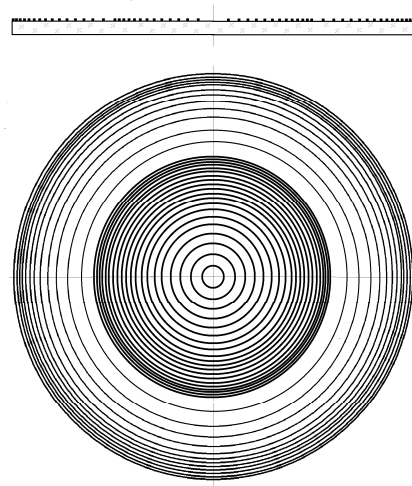


Fig. 1. Sectioned gradient circular grating, consisting of two groups of rings.

### III. RESULTS AND DISCUSSION

The formation principle of a break in the wave front reflected from the annular sectioned gradient grating is shown in Fig. 2a, where 1 is the grating, 2 is the incident flat wave front, 3 is the reflected wave front.

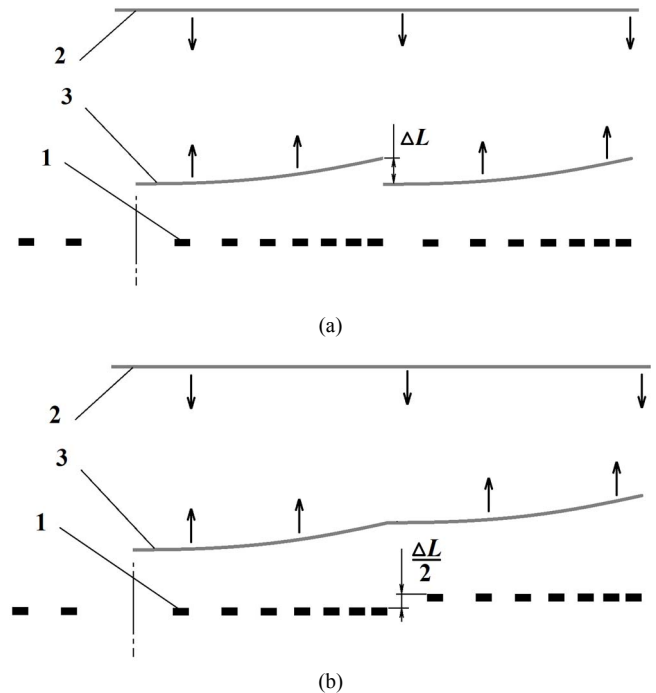


Fig. 2. Reflection of a flat phase front from sectioned gradient grating: a – flat gradient grating, b – stepped gradient grating.

The break of wave front can be defined as  $\Delta L = 2\pi\lambda / \Delta\phi$ , where  $\lambda$  is the wavelength,  $\Delta\phi$  is the difference in phase shifts obtained by the wave during its interaction with the edges of neighboring ring groups of the gradient grating. We propose to perform modified grating with a step  $\Delta L/2$  between adjacent ring groups to obtain smoother reflected wave front (Fig. 2b).

A comparison of the focusing properties of two circular sectioned gradient gratings consisting of two groups of rings was carried out to determine the effect of the step of a sectioned grating on its focusing abilities. One of the gratings

is flat and the second has a step at the boundary of the ring groups. The axial symmetry of ring gratings greatly simplifies the modeling of their properties. Calculation of phase changes in the radial direction provides a complete picture of the focusing properties. An annular grating can conditionally be considered consisting of separate sectors, which are formed by parallel conductors. In this case, the calculation and modeling techniques developed for conventional metal gratings consisting of parallel conductors are applicable. Computer modeling was carried out according to the FDTD method [18], which is presented in the freely available software package "MEEP" [19].

For numerical simulation, a ring grating diameter of 4 mm was chosen. Real THz lasers use gratings having a diameter of about ten times that. A smaller diameter of the investigated grating was chosen to obtain a more visual picture of the phase front change. The gratings under consideration consisted of metal strips 20 μm wide. The thickness of the metal layer was 0.5 μm. The sequence of period changes in the radial direction and a stepwise change in the plane are shown in Fig. 3. Both gratings have 40 strips (20 strips on each side). The strips are formed into two groups, in each of which the distances between the ribbons decrease in the direction from the center of the grating. Distance change step is 16 μm. One of the gratings is plane, the second grating has step 50 μm at the boundary between groups of rings.

The results of modeling the interaction of plane electromagnetic waves with gradient gratings are shown in Fig. 4. The arrows indicate the location of the gratings. Calculation results for flat gradient grating are shown at the top of the figure. Results for stepped gradient grating are shown at the bottom of the figure. The plane wave front comes on these gratings on the left. The electric field vector is parallel to the conductors of the lattice. Spatial distributions of the electric field are shown in the figures. Reflected waves interact with incident waves. White color corresponds to zero field intensity. The level of color saturation corresponds to the level of intensity of the electromagnetic field.

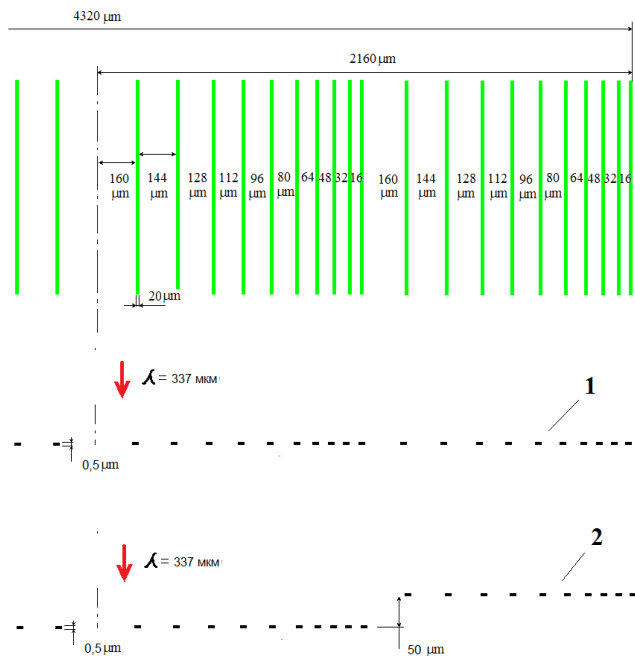


Fig. 3. Schemes of considered gradient gratings: 1 – flat grating; 2 – stepped grating.

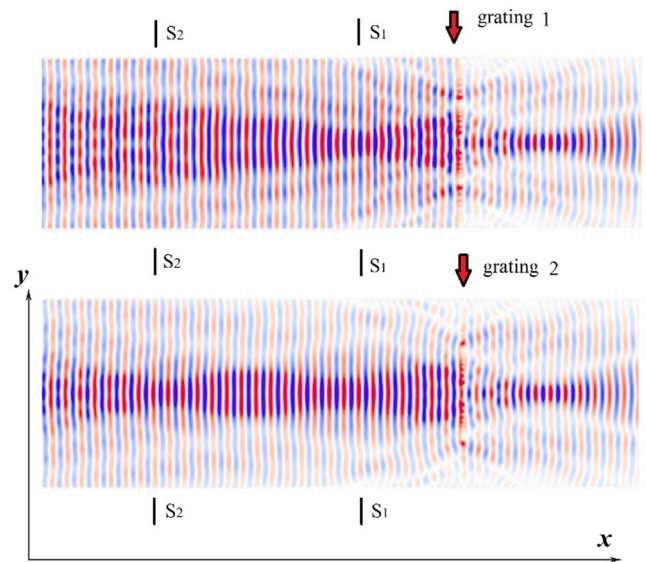


Fig. 4. Spatial distribution of the electric field for two gradient gratings

From the simulation results it is seen that the concentration of reflected radiation in the axial zone is more pronounced when it is reflected from a stepwise gradient grating. The region of radiation concentration in this case is more extended. The shape of the wave fronts of transmitted radiation for both gratings is almost identical. The spatial distribution of the field amplitude along the central axis of symmetry of the system ( $y = 0$ ) is shown in Fig. 5. Arrow indicates the grating position. The interference of the incident and reflected waves is observed to the left of the grating.

The spatial distribution of the field amplitude along the  $Oy$  axis over the section  $S_1$  (Fig. 4) is shown in Fig. 6a. A similar field distribution over section  $S_2$  is shown in Fig. 6b. The given spatial distributions of the amplitude indicate an increase in the radiation concentration along the central axis of symmetry when it is reflected from the stepwise gradient grating 2 in both considered sections.

If a stepwise gradient grating is performed on a transparent substrate, then a similar effect of increasing the axial concentration of radiation can also be obtained for radiation passing through the grating. In this case steps must be performed on the opposite side of the substrate too. The magnitude of such steps is selected taking into account the refractive index of the substrate material.

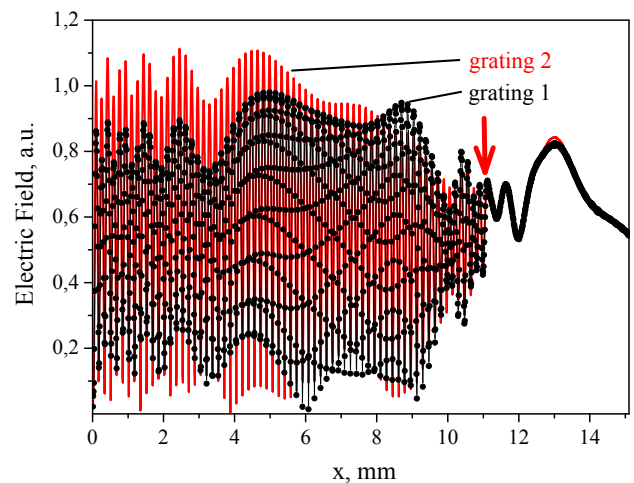


Fig. 5. Longitudinal spatial distribution of the electric field amplitude.

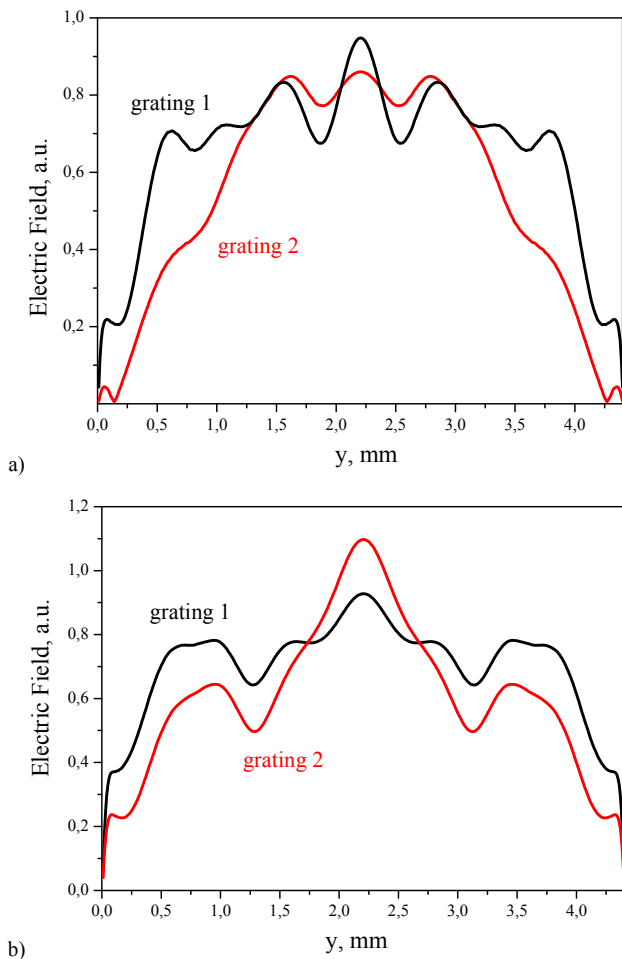


Fig. 6. The spatial distribution of the field amplitude along the  $Oy$  axis: a – along the cross section  $S_1$ , b – along the cross section  $S_2$ .

#### IV. CONCLUSION

As a result of the studies, it was found that the focusing properties of sectioned circular gradient gratings can be improved by giving them a stepped shape. This allows expanding the scope of gradient gratings. In particular, to solve the problem of focusing laser radiation on point objects. In addition, when the laser radiation interacts with a stepwise gradient grating, a radiation concentration region elongated along the central axis is observed compared with a flat gradient grating. This property can find practical application and is for further study.

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