

Transmissive diffractive elements for the terahertz spectral range

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Abstract

The features of vacuum hot-pressing for manufacturing special transmissive diffractive elements (SDEs) for the terahertz (THz) spectral range are described. The characteristics of the experimental SDE samples are studied. The influence of the radiation absorption on the size of the focal spot is estimated.

Keywords: Diffractive optical elements, free electron laser, terahertz radiation, polypropylene

1. Introduction

At present one can observe fast development of the research line in modern science connected with the use of terahertz radiation. Utilizing the THz radiation requires solutions for a number of complicated technical problems regarding generation, control and detection of the waves of the submillimeter range. To control the terahertz radiation one often uses massive off-axis parabolic mirrors. But the mirrors' capabilities for forming focal region with predetermined energy distribution in them is quite limited. Thus, developing SDE to serve that purpose is regarded as crucial [1]. The characteristics of usable radiation are a key factor one to take into account when developing an SDE. The transmissive SDEs observed in the article are intended for controlling the free electron laser radiation (FEL) [2] at the working stations of Siberian Center for Photochemical Research and Technologies of Siberian Branch of the Russian Academy of Sciences. The FEL radiation has the beam of ~ 100 mm in diameter, the pulse duration of ~ 70 ps, its operating wavelength can be tuned in the range of $0,12 \div 0,22$ mm. The coherence length of the radiation is equal to $\sim (1 \div 3)$ cm, which correlates with the length of the light pulse. At such coherence length of the utilizing SDEs becomes possible. At the same time ultimately high average radiation power (up to 400 watt) superimposes restrictions on choice of the SDE substrate materials and requires preliminary tests to be carried out to determine the absorption coefficient and the damage threshold of SDE. That paper presents the achievements in developing transmissive SDEs for the terahertz spectral range manufactured by vacuum hot-pressing.

2. Calculations of the phase transmission function for SDE

To calculate the phase transmission function for SDE one uses the principle of tautochronism [3]. The elementary type of SDE is a diffractive lens [3], its phase transmission function is calculated from the one for an aberration-free refractive lens by reducing the function to interval $[0, 2\pi)$. In the first diffraction order of SDE a phase transmission

function $\frac{k\rho^2}{2f}$ of a spherical lens in the Fresnel approximation is realized. Here λ is an operating wavelength, $k = \frac{2\pi}{\lambda}$ is a wave number, ρ is radial cylindrical coordinate in the SDE plane and f is SDE focal length.

To determine the effect of the homogeneous absorption in the SDE material on the intensity distribution in the caustic, the numerical simulation of the radiation diffraction by SDE has been carried out. The intensity in the focal plane was calculated in the Kirchhoff - Fresnel approximation. The amplitude of the diffracted field for each point was calculated as a sum of the field's amplitudes, diffracted by the each zone of SDE. The lens absorption regarded as an additional amplitude coefficient of absorption depending on SDE profile depth as $\exp\left(-\frac{\chi d}{2}\right)$, where $d(\rho)$ is SDE thickness depending on the radial coordinate, χ - SDE

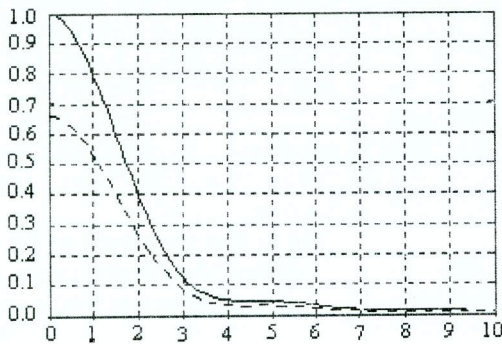


Fig. 1. The transverse intensity distribution in the caustic of SDE with the radius of aperture equal to 37.9 mm and the focal length of $f = 800$ mm, disregarding the absorption (solid curve) and regarding the absorption (dotted curve). ($\chi = 2,35 \text{ mm}^{-1}$). The abscissa indicates the distance from the optical axis.

substrate's absorption factor.

Figure 1 demonstrates the graphs for the intensity distribution in the focus of a diffraction lens disregarding the absorption (the solid line) and regarding the absorption of the material (the dotted curve). One can see that the character of the distribution have remained unchanged and the same goes for the size of the focal spot. The absorption reveals itself as decreasing the peak intensity and decreasing the radiation power in the spot and results in SDE heats up; its zones get deformed and finally destroyed. The aberrations in the focal spot become apparent when SDE diffraction structure is getting deformed.

3. Calculations of the press-mold surface profile

The press-mold profiles are calculated by inversion of the SDE phase function. The structure of the mold surface is coaxial rings, each containing two Fresnel zones. Calculations of the profiles for each of the rings are carried out in MathCAD. For that purpose one determines SDE focal length (f) and radiation wavelength (λ). The profile depth (h) is determined according to the following algorithm:

$$h(\rho) = H(\lambda) \cdot \left(\frac{\text{mod}(\phi(\rho), 2\pi)}{2\pi} \right),$$

where H is the maximum height of the profile, $\phi(\rho)$ is its phase function. In its turn H can be determined as:

$$H(\lambda) := \frac{\lambda}{n_p - 1},$$

where n_p is the material's refractive index and $\phi(\rho)$ can be represented as:

$$\phi(\rho) = \frac{2\pi F}{\lambda} \left[\sqrt{1 + \left(\frac{\rho}{f}\right)^2} - 1 \right]$$

Figure 2 here demonstrates the calculated profile for a press-mold surface in the element's peripheral region.

The accuracy limit for SDE making is defined by the requirement of the low deformation of the formed wavefront in comparison with the radiation wavelength. So the admissible error for the boundary location should not exceed 5 micron, the admissible surface irregularities – 2 micron, the tool angle should secure the width of the reverse slope at the zone boundary on the profile's substrate – no more than 60 micron. The listed errors do not put obstacles in the way of getting the optical focusing quality with the Strehl number equal or more than 0.97.

Aspheric SDEs have monotone phase function that includes polynomials of the radial coordinate in the order exceeding the second. It results in the zones width at the edges of the aspherics is narrower than the one of spherical diffraction lenses. It makes accuracy limits stricter, but if the numerical aperture is about 0.95 and the operating wavelength is equal or more than 130 micron, the errors, indicated above are considered admissible.

The program package for each diffractive element is directly used to program the numerical controlled turning machine, fabricating the press molds.

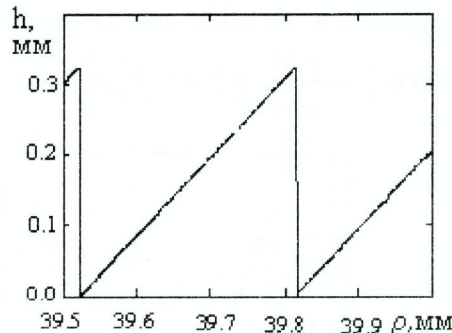


Fig. 2. The press-mold profile in the element's peripheral region with focal length of $f=80$ mm.

4. Transmissive SDE fabrication technology

Pressing is the kernel of SDE fabrication technology. As our experiment has revealed the biggest surface irregularities and uniformities of SDE are caused by the air remaining in the press mold. Hot pressing from sheet materials in vacuum degassing chamber has resulted in sufficient quality of the elements fabricated. The press-mold set is displayed in Fig. 3.

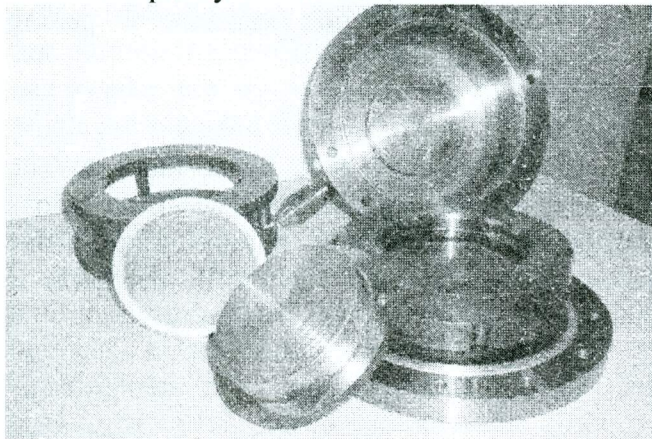


Fig. 3. The press-mold set.

The press form's working surfaces were fabricated by diamond turning at numerical control machines. Making the molds one faced technological limitations in the steepness of the reverse slope due to the tool angle. The fabricated reverse slope with size about 50 micron has resulted in decreasing the element's edge zones diffraction efficiency by 50 per cent. It has not affected the size of the focal spot, but decreased the general diffraction efficiency of the fabricated SDE by 15 per cent.

Figures 4a and 4b are microphotographs of the zero Fresnel zone and the boundary of the first Fresnel zone of the press-mold working surface for SDE with the optical diameter of 75.8 mm and the focal length of 800 mm.

Figure 4a shows improper matching of the end of the diamond tool with the spindle's center of rotation that resulted in the cone-shaped defect of 500 micron height and 120 micron

in diameter at its bottom. In Fig. 4b one can easily distinct the pitch of the grooves, to be about 20 micron.

To fabricate SDE one should use polymer materials with high transmission and significantly low reflection capacity in terahertz diapason. One's best choice [4] is polyethylene, polypropylene and polytetrafluoroethylene (Teflon).

Taking into account the known characteristics of polyethylene one can estimate at what beam power a SDE, fabricated of polyethylene, starts melting. When the SDE is in thermodynamic equilibrium the power density absorbed is equal to the heat of convective outflow from its surface. According to the issues [4], the density absorbed in the wavelength range, one considers here amounts to about 20 per cent (for the element with 2 mm thickness).

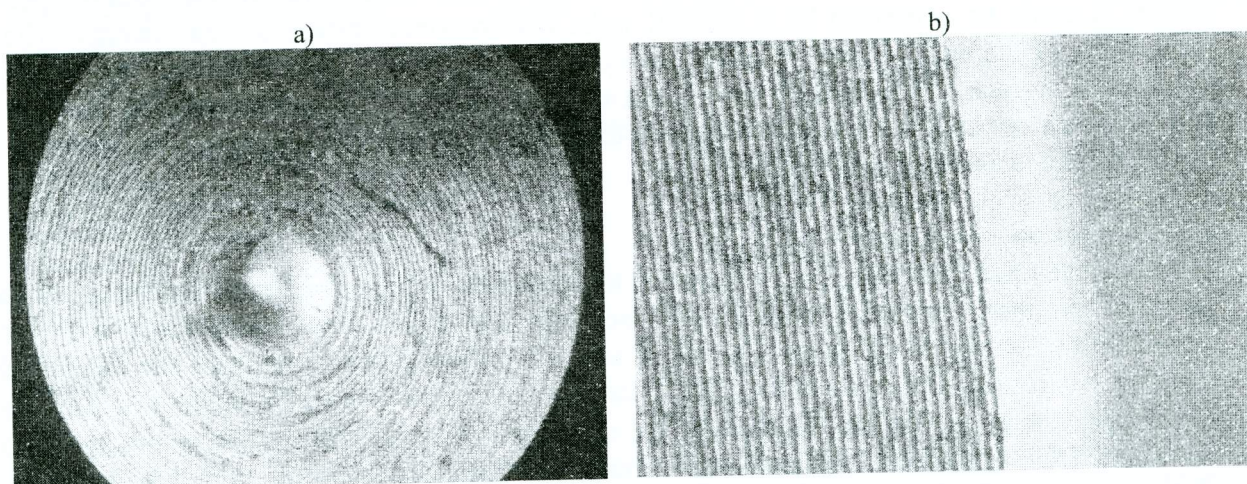


Fig. 4. Microphotographs of the zero zone and the boundary of the first Fresnel zone of the press-mold working surface.

Taking the melting temperature ($T=120^{\circ}\text{C}$) as a maximum service temperature, and the ambient temperature to be $T_0=20^{\circ}\text{C}$ one has the following ratio for radiation intensity I_0 in each point of the element's surface: $0,2I_0 = 2\alpha \cdot (T - T_0)$, where heat exchange coefficient $\alpha = 12 \text{ W/m}^2 \cdot ^{\circ}\text{C}$. What follows is that $I_0 = 12000 \text{ W/m}^2$. The full power capacity amounts to about 94 Watt, if one considers distribution of the radiation beam with 50 mm radius to be homogeneous. The true advantage of the SDEs in comparison with refraction ones is the first could be fabricated in extremely thin substrates with the thickness of about 380 micron. In this case the radiation resistance will be higher than one has just estimated.

A number of the experimental samples made of polypropylene and other organic glasses has been fabricated and tested.

5. Experimental study of SDE optical characteristics

The study of the optical characteristics of the SDEs fabricated was carried out with FEL. The terahertz radiation was emitted at a metal mirror which reflected it to a polarizer. The latter was used to determine the radiation level required for its undistorted registration

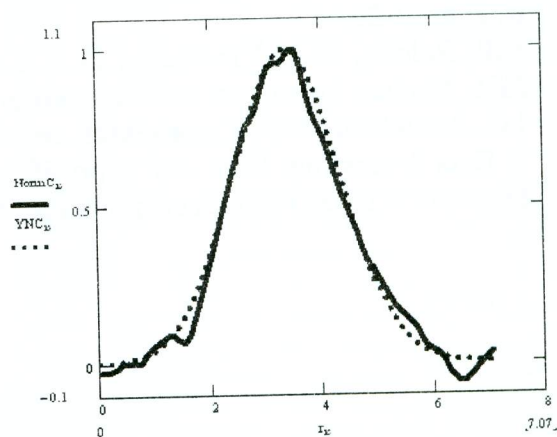


Fig. 5. Luminescence quenching profile in the focal plane of the SDE.

at a luminescent screen.

The screen was being excited by an ultraviolet source. The terahertz radiation was killing the luminescence. The effectiveness of the quenching in each point of the screen was directly proportional to the decreasing local power of the radiation. A CCD camera was utilized to register the changes in the luminescence. Figure 5 displays the changes in the quenching profile after related normalizations in the focal plane of the lens (solid curve); and the Gaussian distribution (dotted curve). The focal spot measured at level $1/e^2$ has been 2.7 mm. If the radiation filled the optical diameter in part one could observe the spot getting wider.

A test of the SDEs are being exposed with the 100 Watt free electron laser beam has revealed dependence of the radiation resistance parameter on the manufacturing errors in the press mold. Local melting was registered in about 6 min in the area of the cone-shaped cavern. It could be explained by a thermal spike due to concentration of stray energy. The local melts of the small elements of the formed SDE structure due to the roughness of the press-mold surface did not result in significant degradation of the focal spot. Additional convective air cooling and better condition of the press mold will allow SDE to work properly in 100 Watt free electron laser beam.

6. Conclusion

The developed technology will allow one to fabricate a family of diffraction elements with the predetermined capacities, including those with the outer zones comparable with the wavelength of terahertz radiation. The study into the optical characteristics of the fabricated elements has revealed the values for their focal-spot diameters exceed the diffraction limit by 10÷15 per cent. It may be due to, mainly, the character of energy distribution in the radiation beam and DOE chromatic absorption determined by finite width of the radiation spectrum. Optimization and further development of the technology will allow one to have FELs equipped with the changeable SDE of high radiation stability.

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