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Excitation of luminescence by a Bessel radiation beam for detection of radiophotoluminescent images with a high spatial resolution

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***Abstract*. A system is proposed for excitation of luminescence with the help of diffraction axicons with a ring aperture to detect luminescent images. The excitation beams are visualised using LiF crystal radiophotoluminophores. It is shown experimentally that spatially truncated Bessel beams formed in this case provide the local excitation of luminescence in the region of diameter 1.6 μm and length 3 mm.**

Keywords: *Bessel beams, deep luminescent images, radiophotoluminophores.*

1. Introduction

We reported earlier the study of new materials, alkali-halide crystals doped with modifying impurities, used for X-ray imaging [1]. The X-ray image is produced by the exposure of a crystal resulting in the formation of luminescent centres. Upon excitation of luminescence of the latent centres, the image is visualised and can be detected, for example, photoelectrically. Upon excitation of the crystals and their storage at room temperature, the luminescent centres are stable, allowing the repeated read-out without the loss of information.

The image can be erased by the crystal heating to 400 – 500 °C. These materials provide the diffraction-limited spatial resolution of the order of 1 μm and the dynamic detection range over 10^4. The parameters of the materials permit their use in high-resolution X-ray micrography.

However, because the detection of images of dense or thick objects requires the use of hard X-rays, the spatial resolution can be deteriorated due to an increase in the so-called depth of the luminescent image. When the X-ray wavelength changes from 10 Å to fractions of angstrom, the image depth changes from tens of microns to several millimetres. For this reason, the observation of images with the limiting resolution by usual methods of luminescence microscopy is possible only for low-density objects [1]. Therefore, X-ray microscopy of any objects with the resolution of the order of 1 μm is impossible without a special development of the methods for detecting deep luminescent images. One of these methods is considered in this paper.

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2. Experimental

The use of microobjectives upon uniform illumination of a crystal by exciting radiation cannot provide a sharp imaging of an extended object along the objective axis. The depth of focus T of an objective and the limiting resolution d_0 are described by the expressions

$$T = \frac{n\lambda}{2A^2},$$

$$d_0 = \frac{\lambda}{2A},$$

where λ is the wavelength of light; n is the refractive index of a medium; and A is the numerical aperture of the objective [2]. For $d_0 = 1$ μm and $\lambda = 0.8$ μm (for F_2-centres in LiF), we obtain the minimum aperture of the objective equal to 0.4 and the depth of focus equal to 2.5 μm upon imaging in air. The consideration of the refractive index of the crystal and the use of an immersion medium can enhance the depth of focus to 3 – 4 μm, which is, however, insufficient for sharp imaging at depths 1 – 2 mm.

This problem can be solved by exciting luminescence by spatially truncated zero-order Bessel beams formed by axicon systems [3]. Such beams do not have the diffraction broadening within finite focal distances. For this reason, the axicon systems provide a small cross section of the central lobe of the beam. The diameter of this cross section is comparable with the limiting spatial resolution of an X-ray sensitive medium and does not virtually change along the entire focal length of several millimetres. When a lens and axicon are illuminated by a collimated light beam with the uniform intensity distribution over its cross section, the longitudinal (Δf_L, Δf_a) and transverse (D_L, D_a) dimensions of the regions of focusing at the 0.5 level are determined for the lens and axicon in the paraxial approximation by the expressions

$$\Delta f_{\mathrm{L}} \approx \frac{1.77\lambda n}{A_{\mathrm{L}}^2}, \quad D_{\mathrm{L}} \approx \frac{0.514\lambda}{A_{\mathrm{L}}},$$

$$\Delta f_{\mathrm{a}} \approx \frac{(r_1 - r_2)n}{A_{\mathrm{a}}}, \quad D_{\mathrm{a}} \approx \frac{0.359\lambda}{A_{\mathrm{a}}},$$

respectively, where A_{L} and A_{a} are numerical apertures of the lens and axicon, respectively $A_{\mathrm{a}} \approx \lambda/d$; d is the period of the diffraction axicon grating; and r_1 and r_2 are the inner and outer radii of the ring aperture of the axicon.

We used a diffraction axicon with a ring aperture. The phase ring diffraction grating of the axicon had a period of 2 μm and radii of the ring aperture 1.38 and 1.84 mm. The grating topology was synthesised using the laser thermochemical direct recording technology, which was developed at Institute of Automatics and Electrometry, Siberian Division, Russian Academy of Sciences. The recording was performed on a chromium film of thickness 0.1 mm deposited on a quartz substrate. A phase grating was produced by dry plasma-chemical etching of quartz, the etching depth being chosen for obtaining the maximum intensity of a central beam and suppressing even parasitic diffraction orders.

For the parameters of our axicon ($r_1 = 1.38$ mm, $r_2 = 1.84$ mm, $d = 2$ mm), the calculated parameters of the region of focusing for $\lambda = 0.456$ μm and $n = 1.396$ were $\Delta f_{\mathrm{a}} \approx 2.8$ mm and $D_{\mathrm{a}} \approx 0.72$ μm. For the lens at the same aperture, wavelength, and refractive index, we had $\Delta f_{\mathrm{L}} \approx 22$ μm and $D_{\mathrm{L}} \approx 1$ μm. Therefore, unlike the lens focusing system, the use of an axicon provides the excitation of luminescence within a cylindrical region of micron diameter over the entire depth of the luminescent image (1–2 mm), which should reduce the contribution from luminescence emitted by neighbouring regions to the luminescent signal detected from the micrometer-size region under study. In addition, the use of the axicon enhances the imaging efficiency because focusing of laser radiation in the micrometer-size region enhances the luminescence intensity.

We studied the efficiency of this method using the setup built for this purpose (Fig. 1). A laser beam was collimated and its diameter was increased with the help of a beam expander consisting of a microobjective (*1*), a diaphragm (*2*), and a collimating lens (*3*). The collimated laser beam was focused by a diffraction axicon (*4*) on a sample (*5*). A microscope (*6*) formed the crystal image in the CCD-array plane, the requi-red part of the image being separated with a diaphragm (*7*). A filter (*8*) separated the luminescence region and suppressed the exciting radiation. Luminescence was excited by a 0.456-μm line from an argon laser, which was optimal for excitation of a LiF–Ca luminophore that we used in experiments. The numerical aperture of the microscope objective considerably exceeded that of the axicon to prevent vignetting.

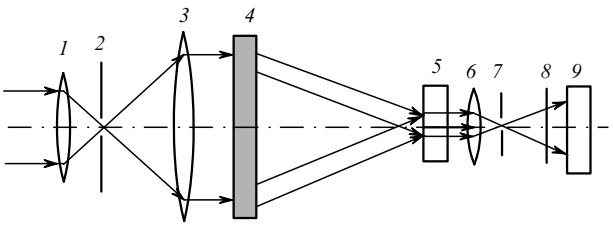

Figure 1. Scheme of the experimental setup for studying the spatial parameters of exciting radiation: (*1*) microobjective; (*2*, *7*) diaphragms; (*3*) collimator; (*4*) axicon; (*5*) sample; (*6*) objective (*8*) optical filter; (*9*) CCD camera.

The shape of the longitudinal section of the exciting radiation beam was detected with an additional CCD camera, which detected the luminescent image from the crystal end. The beam was visualised with the help of a LiF crystal, which was uniformly illuminated by synchrotron radiation. Because of a high resolving power of the material under study, we can assume that the luminescent image exactly repeats the shape of the exciting radiation beam.

3. Results and discussion

Typical images obtained upon visualisation of the longitudinal exciting radiation are shown in Fig. 2. In accordance with the theory, the length of the region of focusing for standard microobjectives (Figs 2a, b) is almost two orders of magnitude less than that for the diffraction axicon (Fig. 2c). Note that the intensity distributions in Fig. 2 were obtained by observing radiation in a nonluminescent crystal along the beam axis.

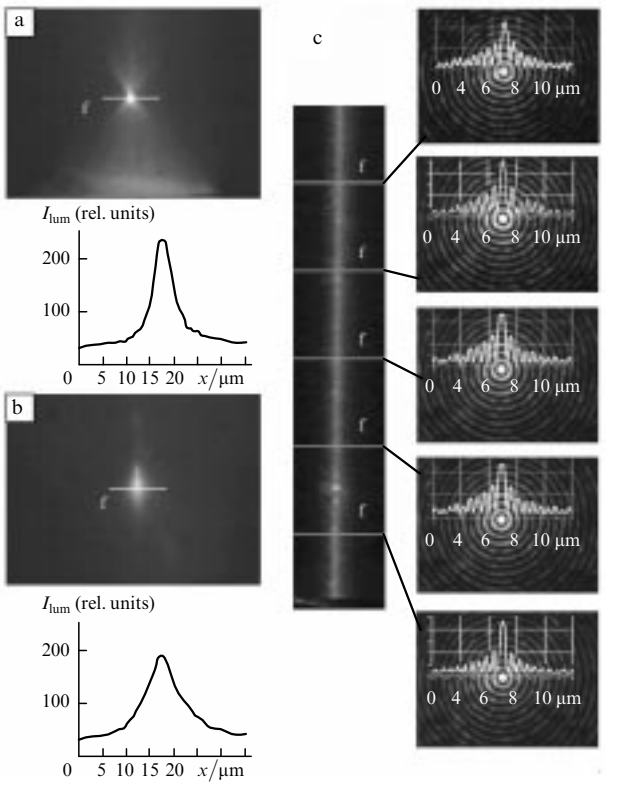

Figure 2. Luminescent image of the longitudinal sections of the region of focusing for different optical systems and the corresponding distributions of the exciting light intensity along the cross-section line f in a LiF crystal obtained using microobjectives with magnifications 6.2×, $A = 0.65$ (a) and 20×, $A = 0.40$ (b), as well as the differential axicon with a ring aperture ($A = 0.23$) (c).

The diameter of the cross section of the central lobe of a Bessel beam in our experiments was 1.6 μm (at the zero-intensity level), which is close to the calculated value 1.53 μm. The longitudinal size of the region of focusing in the LiF crystal was 3 mm. No change in the shape or broadening of the central part of the Bessel beam was observed in luminescence. However, due to the presence of side interfe-

rence maxima, the structure of the Bessel beam represents a system of concentric circles with the maximum intensity at the central region, which gradually decreases away from the centre. For this reason, the exciting radiation in the side lobes of the Bessel beam is summed and the background level increases (Fig. 2c). One can see from Fig. 2c that the intensity at the minima of the diffraction pattern does not vanish, which can be explained by the grating imperfection and the contribution of radiation from the beam regions outside the region of focusing.

Assuming that the grating quality is almost perfect, we can estimate the relative intensities of the Bessel-beam components, by subtracting the background signal from the total signal. Our estimates showed that the background intensity at the central region was 13 % of the central-maximum intensity, while the intensity of the first side lobe was 22 %. This value is close to the calculated one: the ratio of the intensities of the first side and central maxima for a perfect grating is 0.16. This means that the background signal is related to radiation from the regions outside the region of focusing.

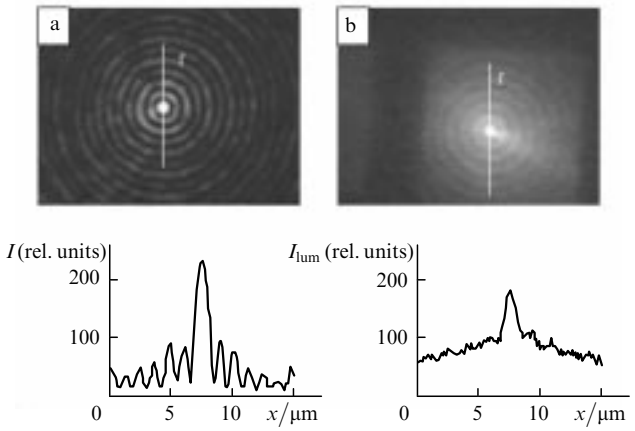

Figure 3. Image of the light field and the intensity distribution along the cross-section line f in a LiF crystal: (a) the exciting Bessel beam and (b) the luminescence signal from a latent X-ray image produced by synchrotron radiation (a net with the 7-μm period). The size of the central region of the Bessel beam is ~ 1.6 μm.

Upon detection of luminescence, the signal-to-background ratio was substantially lower (Fig. 3b). This can be explained by the fact that, unlike the laser beam shaped by the axicon, luminescence of the produced centres is uniformly emitted in all sides. In addition, the region where the emission is collected using the lens detecting system is much greater than that in the case of the axicon because the aperture of the lens system greatly exceeds that of the axicon. The luminescence reflected from the upper and lower faces of the crystal also contribute to the detected signal, resulting in the enhancement of the background. As a result, incoherent radiation collected within a large solid angle, which is excited by the side lobes of the Bessel beam, is summed, the image background increases, and the image contrast decreases. One can see from Fig. 3b that in this case, a sharp signal from the central part of the beam is observed against the intense background. At the same time, the comparison of Figs 3a and b shows that no broadening and change in the shape of the central lobe occur in the luminescent signal from the Bessel beam.

4. Conclusions

We have demonstrated that Bessel beams can be efficiently used to excite luminescence for detecting deep luminescent images. Unlike excitation with the help of lens systems, we used an axicon for uniform excitation of luminescence over the entire thickness of the image by laser beams with an extremely small transverse size. In combination with the materials developed by us and an appropriate image detection system, this makes it possible to realise devices for X-ray micrography using hard X-rays. At the same time, to detect deep images, not only the system for luminescence excitation should be developed but also the optical system eliminating the contribution from the side lobes to the collected emission.

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References

1. Dolbnya I P, Kulipanov G N, Lyakh V V, Makarov O A, Pindyurin V F, Kochubey D I, Kochubey V I, Gorin G B, Gyunsburg K E, Zvezdova N P *Nucl. Instrum. Methods Phys. Res., Sect A* **359** 376 (1995)
2. Rusinov M M, Grammatin A P, Ivanov P D, Andreev L N, Agal'tsova N A, Ishanin G G, Vasilevskii O N, Rodionov S A *Vychislitel'naya optika* (Computational Optics) (Leningrad: Mashinostroenie, 1984)
3. Durnin J *J. Opt. Soc. Am. A* **4** 651 (1987)