NEW INSTRUMENTS AND MEASUREMENT METHODS

Wide-band x-ray optics with a large angular aperture

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Grazing-incidence x-ray optics is briefly reviewed and shown to have several interesting properties. Capillary focusing systems which make use of multiple reflection of x rays are described. This optics is of interest in surface research, medicine, etc.

1. INTRODUCTION

The problem of controlling x-ray beams is of much current interest in connection with the development of many scientific and technological directions, e.g., x-ray microscopy, x-ray astronomy, x-ray plasma diagnostics, and x-ray lithography. Recent advances in the development of intense x-ray sources (synchrotron radiation, pinch and laser sources, and the channeling sources) can, if x-ray focusing systems are available, substantially increase the density of the x radiation at the objects being bombarded. This opportunity is extremely promising in plasma physics, solid state physics, laser technology, and medicine.

The development of an optics for the x-ray range, however, runs into several difficulties, which are quite different from those in the visible and IR ranges. The difficulties stem from the circumstance that the surfaces of all known materials have very low reflection coefficients for x radiation at large angles of incidence. One way to overcome this difficulty is to develop a grazing-incidence optics, based on the phenomenon of total external reflection of the x rays. The grazing-incidence mirrors which have already been developed, which are used in x-ray telescopes and microscopes and which are second-order surfaces, operate on the basis of one or two reflections and have an extremely small angular aperture because of the small value of the total-external-reflection angle. On the other hand, diffraction and interference elements such as Bragg and multilayer mirrors, zone and phase plates, and gratings are spectrally selective and cannot be used to control x-ray beams having a wide spectrum.[1]

Some fundamentally new possibilities have been opened up by the development of the x-ray optical elements, proposed by Kumakhov,[2] which make use of multiple reflections of the x radiation from surfaces with certain special shapes. The various x-ray systems developed along this approach can control x-ray beams over wide frequency and angular ranges.

One specific realization of this suggestion might be the development of focusing systems made up of a large number of curved hollow capillaries. As x rays propagate along these capillaries they are repeatedly reflected from the inner walls. As a result, the total angle through which the x radiation is turned is determined by the curvature of the waveguide; it can be far larger than the critical angle for total external reflection, θ_{cr}. Depending on the arrangement of the capillaries, such systems can transform an x-ray beam with a large initial divergence into an approximately parallel beam or into a converging beam. Various x-ray optical systems developed by this approach could be used to solve many applied problems: producing x-ray images of objects, turning x radiation through large angles, concentrating intense radiation in a small area, reducing the angular divergence of an x-ray beam, etc.

Everything which we have said about capillaries can be extended to systems of reflecting surfaces.

The development of focusing systems of this type was preceded by numerous experiments on the transmission of x radiation of various energies through straight and curved hollow tubes (e.g., Refs. 3–6). We should also call attention to the study by Leĭkin *et al.*,[7] who successfully used multiple total external reflections to develop a so-called slit-free collimator for x rays. We would also like to call attention to an earlier study by Lely and Rijssel,[8] who also discussed the possibility of using multiple reflections in x-ray optics.

In addition to capillary x-ray optical systems it would also be possible to fabricate (by sputtering, for example) focusing periodic structures in which layers of light and heavy elements alternate. The layers of light elements would serve as the "channels" for the radiation, while the heavy layers would reflect it. The period of the reflecting structure should be no less than c/ω_p, where ω_p is the plasma frequency of the material of the reflecting surface, and c is the velocity of light. This condition must be imposed in order to achieve total external reflection in the x-ray and γ-ray ranges. Figure 1 shows the geometry of the focusing by layers of this sort. The first system focuses radiation in one dimension, and the second focuses it in a perpendicular dimension. Periodic focusing systems of this sort are better for use in γ-ray optics, since γ rays can pass fairly well through the layers made of the light elements.

2. CAPILLARY X-RAY OPTICS SYSTEMS

We will take a detailed look at capillary x-ray optical systems, which, as we have already mentioned, make it pos-

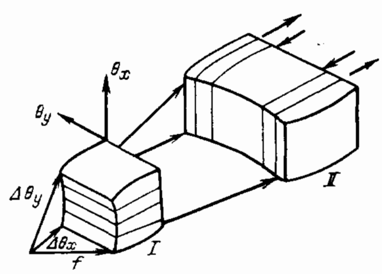

FIG. 1. The focusing of radiation by periodic layers.

sible to shape effectively x-ray beams of a desired configuration over a wide energy range and which have the further advantage that they are structurally simple and amenable to fabrication processes. We will also propose a method for calculating the characteristics of such systems. The method is based on experimental data.

Studies have shown that the inner surfaces of straight and curved glass capillaries are completely suitable for use in x-ray optics. Capillaries of this sort can thus serve as effective x-ray waveguides; i.e., they can be used to transport incident radiation with a fairly broad spectrum with a loss which becomes important only after an extremely large number of reflections, since the loss per reflection can be kept to a level of the order of 1% through an appropriate choice of the capillary material and the finish of the inner surface. The capillary material is responsible for a selective absorption of radiation of certain wavelengths, which are characteristic of the elements in the surface layer. The choice of reflector material thus reduces to eliminating any such elements which would affect the spectral range being used.

One of the basic factors determining the characteristics of a system in the x-ray range is the degree to which the radiation is captured by a single curved waveguide. The curvature of the waveguide is conveniently described by the dimensionless parameter

$$\gamma = \frac{R\theta_{cr}^2}{4r}, \tag{1}$$

where θ_{cr} is the critical angle of total external reflection, r is the radius of the inner aperture, and R is the radius of curvature. From geometric considerations we easily find that for radiation which is incident on the capillary in the direction parallel to the axis of the capillary the condition for total external reflection over the entire channel cross section is $\gamma \geqslant 1$. At $\gamma < 1$ part of the radiation strikes the channel walls with a glancing angle greater than θ_{cr} and is therefore lost at the very first reflection. Consequently, at $\gamma < 1$ the curved waveguide "captures" and transports not all the radiation incident at its entrance but only the part which corresponds to the hatched part of the channel in Fig. 2. The boundary of the capture zone is determined by the equation

$$y(x) = [R + (r^2 - x^2)^{1/2}]\left(1 - \frac{r^2 \sin^2\theta_{cr}}{r^2 - x^2}\right)^{1/2}, \tag{2}$$

and the radiation capture coefficient $\varkappa$ of the curved capillary, which is found from geometric considerations as the ratio of the hatched area in Fig. 2 to the area of the entire channel, is calculated from

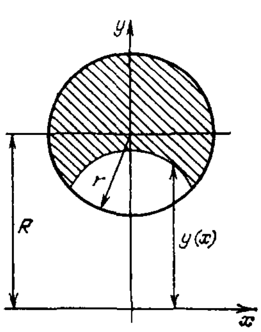

FIG. 2. Filling of the cross section of a curved capillary by radiation in the case $\gamma < 1$.

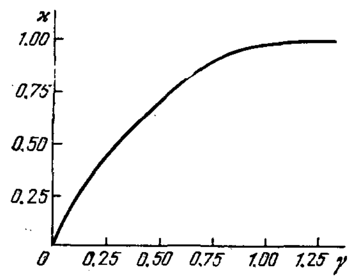

FIG. 3. Calculated geometric radiation capture coefficient $\varkappa$ as a function of the parameter γ.

$$\begin{aligned} \varkappa &= 1 \quad \text{for} \quad \gamma \geqslant 1, \\ &= \frac{1}{\pi}\left[\pi - 2\psi - \sin 2\psi + 4\gamma \ln \frac{1+\mathrm{tg}(\psi/2)}{1-\mathrm{tg}(\psi/2)}\right], \\ \psi &\equiv \arccos \gamma^{1/3}, \quad \text{for} \quad \gamma < 1. \end{aligned} \tag{3}$$

The $\varkappa(\gamma)$ dependence in Fig. 3 is a universal one since it does not explicitly contain the specific geometric parameters of the capillary or the energy of the radiation.

Figure 4 shows capture-zone boundaries constructed from expression (2) for various values of the parameter γ. Figure 5 shows photographs of an x-ray beam recorded at the exit from a uniformly curved capillary for various values of the radius of curvature. A careful comparison of the shapes of the experimental and calculated "half-moons" for the various values of γ reveals that they are essentially the same, except near the "horns," which are rounded in the photographs, rather than sharp.

With increasing energy of the γ rays, the radiation capture coefficient of a curved capillary decreases because of the decrease in the critical angle for total external reflection, in accordance with (1) and (3). Consequently, the efficiency of a specific capillary focusing system in the high-energy region can become negligible, because the individual capillaries are only slightly filled by the radiation. This circumstance means that in the hard x-ray range it is necessary to construct a system from capillaries with waveguiding channels which are as small as possible, so these channels can be filled with radiation more successfully.

3. TURNING OF X RADIATION

In capillary x-ray optical systems, the radiation is turned through large angles. Accordingly, a calculation of the efficiency of such systems must incorporate, in addition

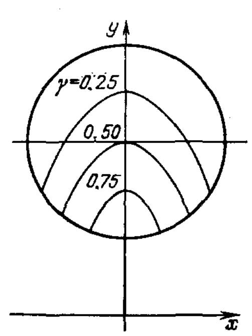

FIG. 4. Boundaries of the zone in which radiation is captured by a curved capillary for various values of the curvature parameter.

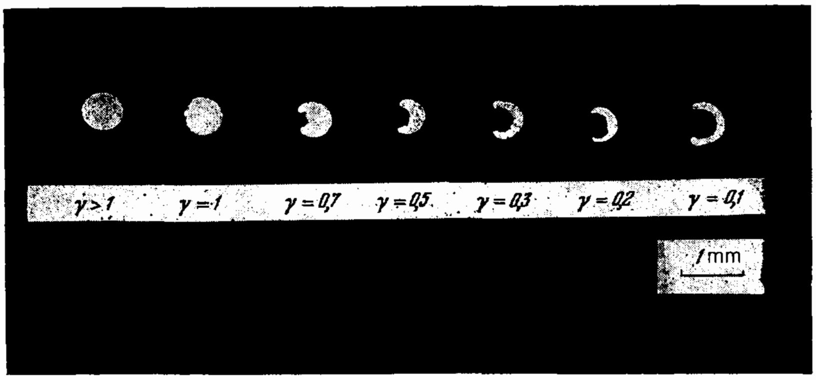

FIG. 5. Distribution of radiation over the cross section of a capillary for various values of the curvature parameter.

to the incomplete capture of radiation by the individual capillaries (which we discussed in the preceding section), the subsequent attenuation of the radiation upon repeated reflections. The radiation which is captured into the channel is turned through the curvature angle of the capillary, Φ, as a result of reflections from the walls. The attenuation of the radiation can be estimated from the attenuation coefficient[9]

$$R_\Phi \approx \exp(-\beta\alpha^{-3/2}\Phi),$$

where α and β are determined by the real and imaginary parts of the refractive index of the material,

$$n = 1 - \frac{\alpha}{2} + i\frac{\beta}{2} \quad (\alpha,\ \beta \ll 1). \tag{4}$$

The attenuation coefficient R_Φ is a characteristic of the reflection capability of a material for turning radiation through a given angle Φ. Values of this coefficient were calculated in Ref. 10 for various materials over a wide range of γ-ray energies. Results calculated for $\Phi = 0.25$ rad are shown in Fig. 6. They demonstrate that it is possible in principle to turn hard x radiation through a significant angle without a major loss. Furthermore, the largest values of R_Φ correspond to specifically the hard x-ray range, so it is possible in principle to develop a grazing-incidence x-ray optics operating on the basis of multiple reflections.

We introduce the concept of the "throughput" of the system, which we define as the ratio of the radiation power at the exit from the system to the power incident at the entrance to the system. The throughput is obviously a characteristic which incorporates all types of loss of radiation in the system. In order to increase the throughput it is necessary to reduce the thickness of the capillary walls and to choose the best dimensions and material for the capillaries. At high energies, the throughput of a specific system begins to fall off because of a decrease in the radiation capture by the individual capillaries. At low energies ($E \lesssim 1$ keV), the throughput of the system again falls off, because of an increase in the absorption of the radiation in this range. Each specific capillary system thus has a natural working passband, which can be $\sim$10–20 keV according to calculations.

Measurements which have been carried out over the energy range 0.5–1.5 keV in synchrotron radiation in vacuum and at 4-40 keV in the radiation from an x-ray tube in air prove that capillary x-ray optical systems are highly efficient for turning and transporting radiation. This efficiency is not attainable by any other known methods.

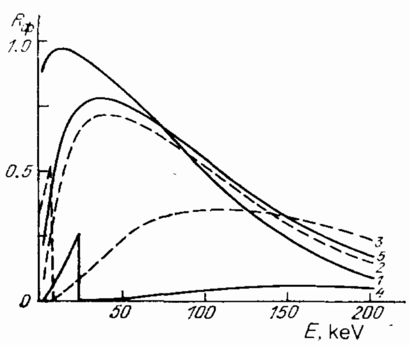

FIG. 6. x-ray attenuation coefficients for turning through an angle $\Phi = 0.25$ rad by a curved cylindrical surface. 1—Be; 2—Al; 3—Cu; 4—Ag; 5—S-52 glass.

4. X-RAY LENS

As an example we will describe a focusing x-ray system[11] which captures radiation from a source in an angular aperture of 23° and focuses it to a spot of the order of 1 mm in diameter at a distance of 108 cm.

Figure 7 is a photograph of the focusing system. The entire system is 98 cm long and consists of 2000 glass capillaries with an outside diameter of 0.4 mm and a channel diameter of 0.36 mm. The capillaries form a hexagonal close packing in cross section; the area of the channels amounts to 73% of the entire area of the entrance and exit ends of the system. The focal lengths of the system are 5 cm, starting from the ends of the capillaries, and are determined by the inclination of the straight sections of the capillaries with respect to the axis of the system. The straight sections are each 5 cm long. In the central part, the capillaries are uniformly curved to a radius of curvature ranging from 2 m in the outer layer to $R = \infty$ for the straight central capillary. The optimum energy for this system, E_0, is 1.7 keV. At this energy, all the layers of the system should capture the radiation completely. At $E > E_0$, the condition $\gamma \gg 1$ ceases to hold, first for the outer layers, and the geometric capture coefficient $\varkappa$ falls below 1. However, because of the large number of capillaries in the outer layers of this system, their contribution to the energy density of the focal spot remains large.

Tests of the system were carried out in air. The radiation source was a BSV-25 x-ray tube with a copper anode. The minimum radiation energy was 4 keV. The ratio of the energy density in the focal spot to the energy density at the

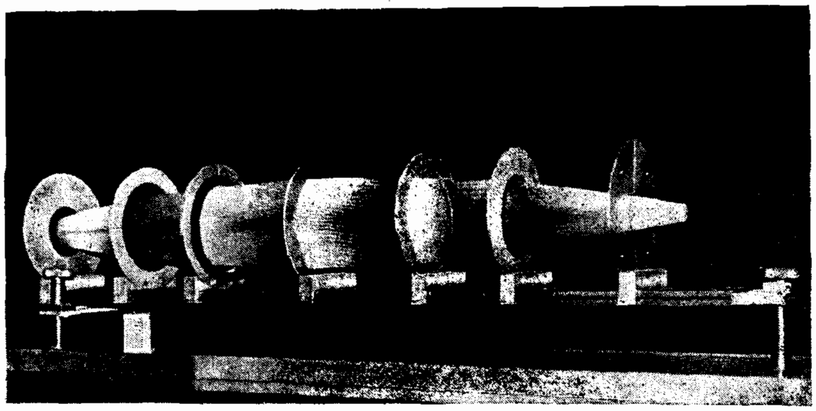

FIG. 7. An x-ray focusing system.

same point in the absence of the focusing system is shown in Fig. 8. We see that the increase in the energy density achieved by the focusing exceeds a factor of 3000 at an energy of 4 keV. The energy density in the focus of the system is an order of magnitude greater than the energy density at the exit from the system. For softer radiation, the efficiency of the system should be substantially higher.

Figure 9 shows x-ray photographs taken at various distances from the exit end of the system. These photographs illustrate the process by which the focal spot is formed and subsequently evolves. We can clearly see an irregularity in the illumination of the channels of the capillaries in the layers and a tendency toward a decrease in the illumination of the outer capillaries in comparison with that of the inner capillaries. The irregularities in the layers stem from various errors in the fabrication of the capillaries and in the assembly of the system. The random filling of the cross sections of the channels by radiation in comparison with Fig. 4 is explained on the basis that the focusing system has straight sections at the ends, where the filling figures shown in Fig. 4 are successfully rereflected.

The outgoing radiation is transformed into a nearly parallel beam by a half-lens, at whose exit the ends of the capillaries are straight and parallel to each other, instead of converging as in the focusing system described above. For example, the divergence of the x radiation in the central part

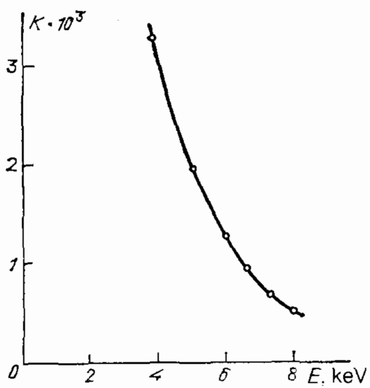

FIG. 8. The factor by which the radiation density is increased versus the energy for the focusing system in Fig. 7.

of the x-ray lens which was fabricated (Fig. 7) decreases by one or two orders of magnitude from the initial divergence (23°), depending on the radiation energy.

Such systems are of interest for astrophysics, x-ray lithography, etc.

Figure 10 shows an example of an x-ray optical system designed for x-ray lithography. This device is, in a sense, the x-ray lens in Fig. 7 which has been cut in half. By analogy with that lens, this system consists of capillaries (in this case 12 000 of them), which together capture the radiation emanating from a point source in a solid angle of 0.25 sr and transform it into a quasiparallel beam (within the angle of total external reflection). This system was designed for an x-ray energy of 1–2 keV; its throughput can reach 50%.

These systems demonstrate the possibility of effectively controlling x-ray beams over a broad spectral range by the methods of capillary x-ray optics. This possibility is not presented by any other existing devices. These systems thus hold promise for applications in science and technology, particularly in combination with intense new sources of x radiation.

5. ENERGY DENSITY OF THE X RADIATION IN FOCUSING SYSTEMS

The most important characteristic of an x-ray focusing system of the nature of the lens described above is its ability to create a high concentration of radiation at a target. Let us estimate the maximum x-ray power density which can be achieved by means of conventional x-ray sources and the focusing facilities which have been proposed.

The diameter of the focal spot in this optics is given by

$$d_f = 2\,(r + f\varphi), \tag{5}$$

where r is the radius of the capillary channel, f is the focal length, and φ is the angle at which the radiation leaves the capillary. In real systems we would have $f \sim 1$ cm and $\varphi \lesssim 10^{-4}$. At the present level of the technology for fabricating multicapillary systems, one could achieve a channel diameter as small as 10^{-4} cm, so the focal-spot diameter which could be attained would be of the same order of magnitude.

We assume that our x-ray source has a power J. The power density of the x radiation can then be calculated from

$$W = \frac{\eta J}{S}, \tag{6}$$

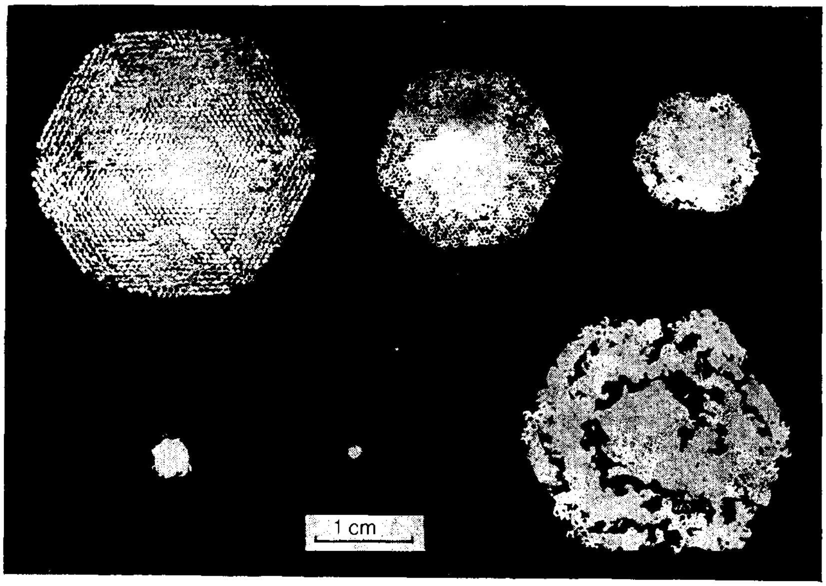

FIG. 9. x-ray distributions at various distances from the exit of a focusing system (in millimeters): a—2; b—20; c—30; d—40; e—50; f—100.

where η is the fraction of the power which is focused, and S is the area of the focal spot.

Analysis shows that the coefficient η ranges from 10^{-2} to $25\cdot 10^{-2}$ in the x-ray range, for an isotropic source.

We consider two examples: 1) $S = 10^{-4}$ cm^2; 2) $S = 10^{-7}$ cm^2. If the source is an x-ray tube, we have

$$J = kiZU^2, \tag{7}$$

where $k \approx 10^{-9}$ V^{-1}, i is the average current, in amperes, Z is the atomic number of the anode material, and U is the tube voltage, in volts. The power of large x-ray tubes ranges from 10 to 100 kW. A fraction of the power of the electron beam ranging from 10^{-4} to 10^{-2}, depending on the voltage, the anode material, and the current, is converted into x radiation. In large x-ray tubes with a rotating anode, the average power of the x radiation can range from several tens of watts to several hundred.

We thus see that with $S = 10^{-4}$ cm^2 and $\eta = 5\cdot 10^{-2}$ it would be possible to achieve a power density $W \approx 5\cdot 10^2 J$ W/cm from a continuous-operation x-ray tube; i.e., it would be possible to achieve $W = 5\cdot 10^4$ W/cm^2 at $J = 100$ W.

The highest x-ray density which has been achieved to date has been achieved in the storage rings of synchrotrons. These are huge installations, with an electron beam energy of 1–2 GeV, a pulsating beam current of hundreds of milliamperes, and a ring radius of the order of 10 m.

A synchrotron can provide a radiation power density on the order of 1–10 W/cm^2. We see that with an ordinary x-ray tube as source the optics which we have been discussing here could provide a significantly higher x-ray power density.

The area of the x-ray spot of synchrotron radiation is usually about 1×0.1 cm^2, i.e., 10^{-1} cm^2. Most of the x radiation can be put in a spot with an area $S \approx 10^{-4}$ cm^2 by a capillary focusing system without losses; i.e., the density of synchrotron radiation can be raised by three orders of magnitude.

These results show that the x-ray optics which we have been discussing here may find widespread use in experimental physics, teamed up with promising sources such as high-

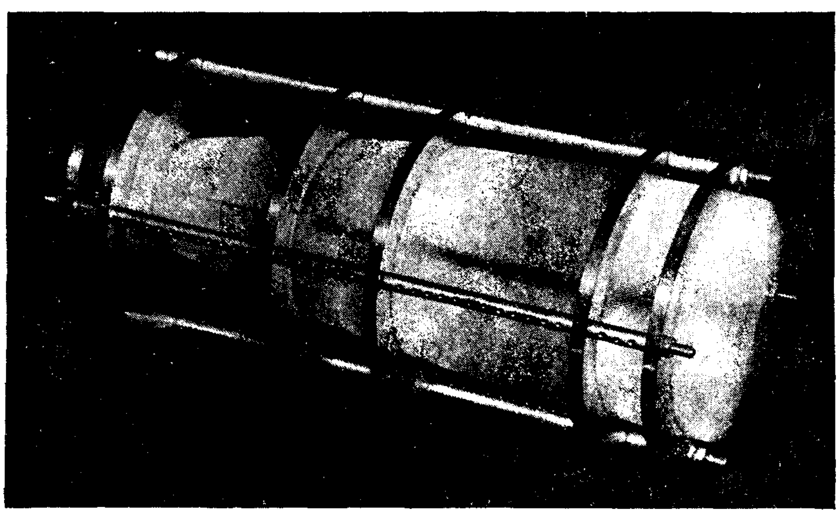

FIG. 10. An x-ray optical system for forming a quasiparallel beam.

power x-ray tubes, synchrotrons, and laser-plasma and pinch x-ray sources.

[1]J. H. Underwood and D. T. Attwood, Phys. Today **34**, No. 4, 44 (April 1984) [Usp. Fiz. Nauk **151**, 105 (1987)].

[2]M. A. Kumakhov, *Radiation by Channeled Particles in Crystals* (In Russian), Energoatomizdat, M., 1986.

[3]P. J. Mallozzi, H. M. Epstein, R. G. Jung, D. C. Applebaum, B. P. Fairand, W. J. Gallagher, R. L. Uecker, and M. C. Muckerheide, J. Appl. Phys. **45**, 1891 (1974).

[4]W. T. Vetterling and R. V. Pound, J. Opt. Soc. Am. **66**, 1048 (1976).

[5]D. Mosher and S. Stephanakis, Appl. Phys. Lett. **29**, 105 (1976).

[6]V. A. Arkad'ev, A. I. Kolomiĭtsev, M. A. Kumakhov, V. V. Labuzov, Yu. P. Chertov, and I. M. Shakhparonov, Poverkhnost', No. 2, 44 (1987) [Phys. Chem. Mech. Surf. (1987)].

[7]V. N. Leĭkin, T. A. Mingazin, and V. I. Zelenov, Prib. Tekh. Eksp., No. 6, 33 (1984). [Instrum. Exp. Tech. (USSR) **27**, 1333 (1984)].

[8]D. A. Lely and T. W. Rijssel, Philips Techn. Rundschau. **13**, No. 4, 96 (1951).

[9]A. V. Vinogradov, V. F. Kovalev, I. V. Kozhevnikov, and V. V. Pustovalov, Zh. Tekh. Fiz. **55**, 244 (1985) [Sov. Phys. Tech. Phys. **30**, 145 (1985)].

[10]V. A. Arkad'ev, M. A. Kumakhov, and R. F. Fayazov, Pis'ma Zh. Tekh. Fiz. **14**, 226 (1988) [Sov Tech. Phys. Lett. **14**, 101 (1988)].

[11]V. A. Arkad'ev, A. I. Kolomiĭtsev, M. A. Kumakhov, V. V. Labuzov, I. Yu. Ponomarev, I. A. Khodeev, Yu. P. Chertov, and I. M. Shakhparonov, Pis'ma Zh. Tekh. Fiz. **14**, 97 (1988) [Sov. Tech. Phys. Lett. **14**, 48 (1988)].

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