Technical Physics Letters, Vol. 30, No. 9, 2004, pp. 784–785. Translated from Pis’ma v Zhurnal Tekhnicheskoĭ Fiziki, Vol. 30, No. 18, 2004, pp. 65–69.
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High-Intensity X-ray Microbeams Obtained Using a Cylindrical Polycapillary Structure

A. Yu. Romanov* and I. V. Dmitriev
Institute for Roentgen Optics, Moscow, Russia
** e-mail: androm2@yandex.ru*

Received March 24, 2004

Abstract—High-intensity quasi-parallel X-ray microbeams with a radiation flux density on the order of 10^{10} photon/(s mm^2) and a divergence of several milliradians, which is close to the parameters of synchrotron radiation, were obtained using a microfocus source based on a transmission-type X-ray tube. The divergent X-ray radiation was converted into a quasi-parallel beam using a cylindrical structure of Kumakhov polycapillary optics with a micron channel diameter. © *2004 MAIK “Nauka/Interperiodica”.*

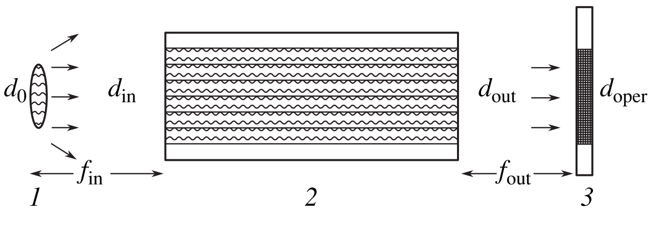
Solving some problems of X-ray microanalysis requires using high-intensity microbeams. In addition, some applications pose limitations with respect to the radiation beam divergence [1]. The problem of obtaining high-flux-density X-ray radiation beams under laboratory conditions is important because conventional high-intensity radiation sources such as synchrotrons and water-cooled X-ray tubes with rotating anode are expensive and not readily accessible. Additional requirements concerning quasi-parallel microbeams make the task even more difficult. A possible solution is offered by X-ray systems implementing Kumakhov polycapillary optics in combination with usual X-ray tubes of the transmission and reflection types. In this way, it is possible to obtain X-ray microbeams with required parameters even using low-power X-ray tubes [2–4].

The possibility of using Kumakhov semilenses for obtaining quasi-parallel beams is well known [2–4]. Using microfocus semilenses with focal distances below 1 mm, it is possible to obtain X-ray sources with a beam divergence on a level of the critical total external reflection angle and a flux density on the order of 10^{10} photon/(s mm^2) for monochromatic radiation (e.g., CuK_α) based on usual X-ray tubes without water cooling [2]. However, the cross-section area of the X-ray beam is determined by the output diameter of a semilens, which is typically on the order of a millimeter. Such dimensions are not suited for some applications of X-ray microanalysis, while placing a diaphragm restricting the beam size past this system significantly decreases the radiation intensity.

There are two possible ways to decrease the beam cross section and increase the radiation flux density in quasi-parallel microbeams. The first way is via improvement of the optical element, and the second, via modification of the X-ray source. We have achieved the desired result by combining both methods. The new possibilities were provided, first, by the development of special microfocus X-ray sources enabling ultimate approach to the focal spot [4] and, second, by the development of a technology of cylindrical polycapillary structures with micron channels [2].

This study was aimed at experimental verification of the possibility to obtain high-intensity quasi-parallel X-ray microbeams using the aforementioned microfocus X-ray source and a polycapillary optical element.

The essence of the proposed method is as follows. The optimized cylindrical polycapillary structure is placed maximally close to the focal spot of a specially modified X-ray tube. An intense X-ray quasi-parallel microbeam is obtained at the output of the polycapillary structure [5]. The experimental optical scheme is depicted in the figure, where d_0 is the focal spot size of the X-ray tube, f_{in} is the focal distance (maximum approach to the focal spot), d_{in} is the input diameter (exposed spot), and d_{out} is the output diameter (output beam size). Using this scheme, it is possible to obtain beams with a diameter determined by the size of the effective focal spot of the X-ray tube and a distance from the focal spot to the input of the polycapillary structure $d_{\text{in}} = d_{\text{out}} = d_0 + 2f\theta_c$, where θ_c is the angle of critical total external reflection from the inner capillary



Schematic diagram illustrating the formation of an X-ray microbeam using a polycapillary structure: (*1*) focal spot; (*2*) polycapillary stricture; (*3*) detector.

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walls. Since the critical angles are small, the increase in the output beam diameter as a result of the divergence of a beam passing through the polycapillary structure is not large. For example, at the distance achieved in our experiments (200 μm) and a radiation energy of 8 keV ($\theta_c \cong 4 \times 10^{-3}$ rad), the corresponding divergence is as small as $d_{\text{incr}} = 2\theta_c f_{\text{in}} = 2 \times 4 \times 10^{-3} \times 200 = 1.6$ μm. The operating beam diameter is also determined by the divergence and the distance to an object: $d_{\text{oper}} = d_{\text{out}} + 2\theta_c f_{\text{out}}$. The divergence of obtained beams was on the order of double critical total external reflection angle. Moreover, according to some data [6], the real divergence is even smaller due to the considerable role of the wave properties in submicron channels.

Owing to the maximum proximity of the polycapillary structure to the X-ray source (in our case, a transmission-type X-ray tube), the input radiation flux density increases and the output beam diameter d_{out} is equal to the diameter of the working zone of a polycapillary structure (exposed spot) d_{in} of a straight-wall cylindrical capillary structure (i.e., the spot size is transmitted without changes) [5]. The straight-wall cylindrical capillary structure provides for a greater transmission than that of a structure with bent channels (such as a semilens). Thus, the polycapillary cylindrical structure (column) with the minimum possible channel size is, probably, among the optimum structures for obtaining high-intensity quasi-parallel X-ray microbeams due to the maximum approach to the focal spot.

The microfocus X-ray source (designed and developed at the Institute for Roentgen Optics, Moscow) was specially optimized for use with polycapillary optics. The source makes use of a BS-11 transmission-type X-ray tube. The electron beam is focused by a system of magnetic lenses. The thickness of a beryllium foil in the exit window was 200 μm. The tube design provides for the maximum approach to the anode: a polycapillary structure can be situated at a distance of $f_{\text{in}} \approx 200$ μm from the focal spot.

The polycapillary cylindrical structure (also developed at the Institute for Roentgen Optics, Moscow) had a minimum column length necessary only for a small-angle collimation (involving several reflections). For example, a column with a capillary diameter of 1 μm provides for 4 reflections of CuK_α radiation over a length of 1 mm, but such short columns are not convenient in use. We used a 1-cm-long column with a capillary diameter of 2 μm and a total structure diameter of 2 mm.

The experiments were performed using an X-ray tube with a copper anode. The maximum tube power for operation without any risk of damaging a target is 10 W. The tube was operated at 25 keV and a current of 10 μA. The measured radiation beam intensity at the output of the polycapillary cylindrical structure was 3×10^5 photon/s. Measurements of the beam size showed that the full width at half maximum intensity was 20 μm. It was established that the tube exhibits a direct dependence of the intensity on the current; for this reason, the intensity was extrapolated to a value per unit power (1 W).

The radiation flux density calculated using the results of measurements was 10^9 photon/(s mm^2) per 1 W of electron beam. Increasing the tube power to 10 W yields 10^{10} photon/(s mm^2), which is comparable with the values for synchrotron radiation sources. For example, FOP synchrotron (ESRF) provides for a flux density of 5×10^{10} photon/(s mm^2) in the energy range from 7 to 21 keV, while ANKA synchrotron (Karlsruhe) yields 10^{12} photon/(s mm^2) in the 4–20 keV range.

Thus, we have obtained high-intensity quasi-parallel X-ray microbeams with a cross-section diameter on the order of 10 μm and a radiation flux density on the order of 10^{10} photon/(s mm^2). The laboratory source is based on a usual transmission-type X-ray tube without water cooling. Additional optimization of the scheme and components will provide for a further increase in the radiation flux density in the beam up to 10^{12}–10^{13} photon/(s mm^2).

Acknowledgments. The authors are grateful to Prof. M.A. Kumakhov and O.V. Mikhin for valuable advice.

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Translated by P. Pozdeev