The phenomenon model of X-ray beam angular divergence decreasing formed by composite waveguide-resonator

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Abstract. The phenomenon of X-ray fluxes waveguide-resonance propagation is presented briefly. There is described simplest design of the planar X-ray waveguide-resonator – device functioned in frame of the phenomenon. Advantages and shortage of the device are discussed in details. Experimental characteristics of the composite planar X-ray waveguide-resonator allowed to decrease the angular divergence of its emergent beam at the integral intensity conservation are presented. Simplified model of this device functioning is formulated.

1. Introduction

It is well known that the X-ray beam diagnostics of materials is the most widespread and universal means of its properties investigation. In the last time, specific devices for the nanosize objects analysis by X-ray methods were elaborated. There are planar X-ray waveguide-resonance structures [1]. Planar X-ray waveguide-resonator (PXWR) is the simplest device from the structures set. Main feature of these devices is the functioning in frame of the waveguide-resonance radiation propagation phenomenon. The phenomenon discovery was result of the creative rethinking of literature data and our systematic experimental investigations.

First stone into the waveguide-resonance radiation propagation phenomenon was laid down by appearing of X-ray slitless collimators [2]. This specific device was formed by two quartz polished planar plates tightly pressed to each other. The slitless channel between its could not let by optical radiation but allowed to transport X-ray fluxes. The next step in this direction was connected with the interference field of X-ray standing wave registration in conditions of X-ray flux total external reflection on the material interface [3]. The conception of the X-ray standing wave interference field introduced into the interpretation approach by prof. Laue for the Borrmann effect description [4] allowed to find the alternative logical explanation of the slitless collimator functioning. Our systematic investigations of X-ray quasimonochromatic flux propagation through the extended slit clearance in conditions of the slit width variation allowed to conclude that the nanosize slit clearance transports X-ray radiation fluxes by the specific mechanism, which did not mention early [5]. We called the mechanism as the waveguide-resonance radiation propagation one and understood that it is the fundamental phenomenon. Devices functioned in frame of the phenomenon we called planar X-ray waveguide-resonators [6]. It is very interesting that our discovery got the independent confirmation in the work of Japan scientist [7]. They studied the propagation peculiarities variation of MoKα monochromatizating radiation flux through the angular reflecting structure formed by polished silicon plates on the angle in the magnitude range 0–0.5 degrees. Its experiments data showed that the sharp increasing of the structure emergent beam intensity at angles near 0.01 degrees can not be explained by well-known effects and mechanisms.

2. X-ray flux transportation by simplest PXWR

Construction of the planar X-ray waveguide-resonator is shown in figure 1. It device captured of X-ray quasimonochromatic flux by its entrance cut in the angular range, which can not exceed the double critical angle of the radiation total reflection for reflectors material, transports the flux almost without attenuation and forms X-ray emergent beam. It is significant that the emergent beam divergence angle is equal to the radiation capture angle. The conception allowed to build the model of X-ray flux waveguide-resonance propagation was based on the revolutionary hypothesis about the uniform interference field of X-ray standing wave in all space of the planar extended slit clearance. This situation is characterized by the principle difference from the multiple flux total reflection in the planar extended slit clearance. The difference is readily illustrated by the figure 2. X-ray flux of the quasimonochromatic radiation in the wide slit clearance undergoes the multiple external total reflection with set appearing of the local interference fields of X-ray standing wave (figure 2(a)). The longitudinal size of local interference areas “c” is defined by half of the radiation coherent length parameter value L in line with the expression [7]:

$$c = \frac{L}{2} = \frac{\lambda_0^2}{2\Delta\lambda_0} \tag{1}$$

where λ_0 is the main wavelength of the radiation, $\Delta\lambda_0$ is the radiation monochromatization degree. The transversal size of these areas is defined by the experimental conditions and is approximately equal to the longitudinal dimensions for the total external reflection phenomenon [8]. Because of the interference field is excited not only in the space above material interface but in the reflector material volumes the minimum flux attenuation can be achieved in conditions of the phase-conjugation consecutive reflections, only. In the conjugation violation case, X-ray flux attenuation increases owing to reexcitation the interference field in reflectors volumes.

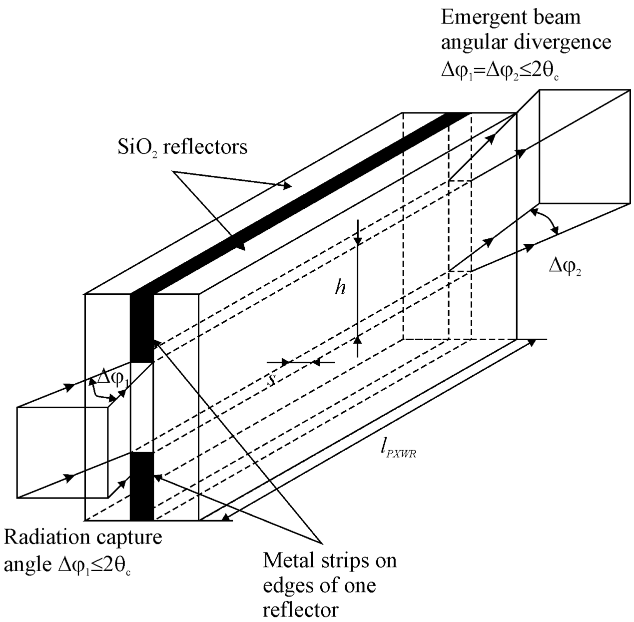

Figure 1. Scheme of X-ray initial flux capture by entrance cut of PXWR simplest design and emergent beam formation by this device.

X-ray flux transportation conditions will change when the distance between reflectors is smaller as half of the radiation coherence length magnitude. This case will be characterized by the local interference field areas confluence and the uniform interference field of X-ray standing wave arising in all space of the planar extended slit clearance (figure 2(b)). The arising of uniform interference field is the necessary and sufficiency condition for the realization of X-ray flux propagation mechanism through the planar extended slit clearance. The mechanism allows to propagate X-ray flux captured under any angles, which are smaller as the total external reflection critical angle transported by the slit clearance almost without attenuation and realized the radiation superfluidity effect.

PXWR of simplest construction demonstrates other specific peculiarities. It is well known that coherence lengths of the characteristic radiation generated by laboratory X-ray sources are characterized by nanosize magnitudes [9]. For example, the coherence length of CuKα radiation is equal to 430 nm. Our systematic investigations of the extended slit clearances emergent beam with distances between reflectors, which were smaller as half of the transported flux radiation showed that beams had nanosize width and heightened radiation density. Its parameter in beams formed by similar waveguides exceeds the radiation density in slit-cut systems emergent beams on 3–4 orders [10]. These facts were very useful for the element material diagnostics improving by TXRF method [11].

In spite of PXWR evident merits this device is characterized by essential shortage. Its emergent beam demonstrates the angular divergence near 0.1 degree. This magnitude is not great but owing it existence the emergent beam losses nanosize width and high value of its radiation density on distance of some centimeters from PXWR outlet. So, the fundamental task of PXWR development is the search of approaches for the angular divergence decreasing.

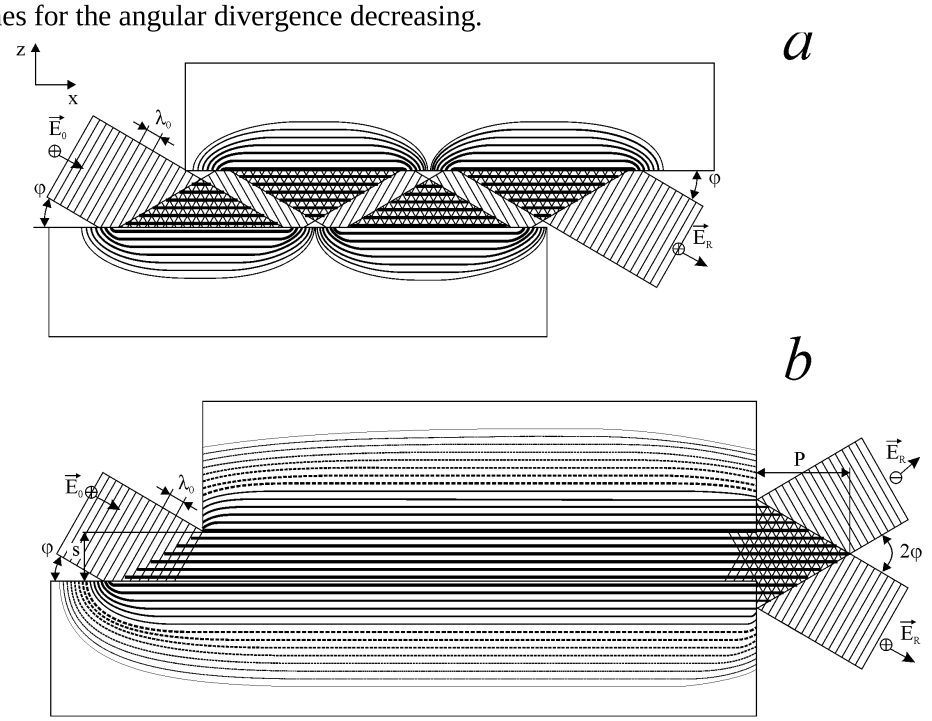

Figure 2. Schemes of X-ray quasimonochromatic flux transportation visualization by the planar extended slit clearance in case of great distance S between reflectors (a) and small magnitude of the distance. P is the protrusion parameter of the uniform interference field.

3. PXWR constructions for angular decreasing of its emergent beams

Experimental search of waveguide-resonance constructions allowed to decrease its emergent beam angular divergence in comparison with the radiation capture angle without reduction of its integral intensity offered to elaboration of modified PXWR designs. Simplest solution of the task was connected with the waveguide-resonance device arrangement by use of nonequivalent length reflectors. In this case, the emergent beam integral intensity does not change but the form of spatial intensity distribution suffers distortion (figure 3(b)). Radiation intensity distribution of emergent beam formed by PXWR with simplest design is characterized by the Gauss outline (Fig. 3a). PXWR construction with nonequivalent reflectors length demonstrate the emergent beam with half-Gauss intensity outline with one half of the outline featured for the waveguide-resonator with simplest construction.

Specific approach allowed to build the original construction completed by two PXWR of simplest design, which were installed one after another on some distance with execution of its mutual alignment (CPXWR) [12]. Experimental data reflected spatial intensity distributions a characteristic for emergent beams formed by the composite PXWR is presented in figure 3(c). CPXWR use for the X-beam formation reduces the spatial distribution divergence magnitude at conservation of the integral intensity and form of the intensity distribution.

Experimental investigations showed that the composite waveguide-resonator demonstrates its unique properties at the specific conditions realization. Conservation of X-ray flux integral intensity is possible if the distance (gap) between PXWRs compiling CPXWR is not exceed the protrusion parameter P (figure 2(b)) defined by the expression [12]:

$$P = \frac{\lambda_0^3}{8\Delta\lambda_0^2} \tag{2}$$

When the gap is higher of this parameter magnitude the construction will produce the small angular divergence. Such construction is not the composite waveguide-resonator. When the gap will be smaller as the interference field protrusion parameter value the interaction possibility of interference fields excited in first and second waveguide-resonators appears. It is precisely, the interference fields interaction leads to X-ray flux integral intensity conservation in the result of partial radiation tunneling in the gap between PXWRs. We displayed that the gap width variation leads to change of the device emergent beam angular divergence. The analytical description of this effect remains to be obtained owing to influence on the effect a form and quality treatment of reflectors butts. At the same time, it is temptingly to propose the model of composite waveguide-resonator function.

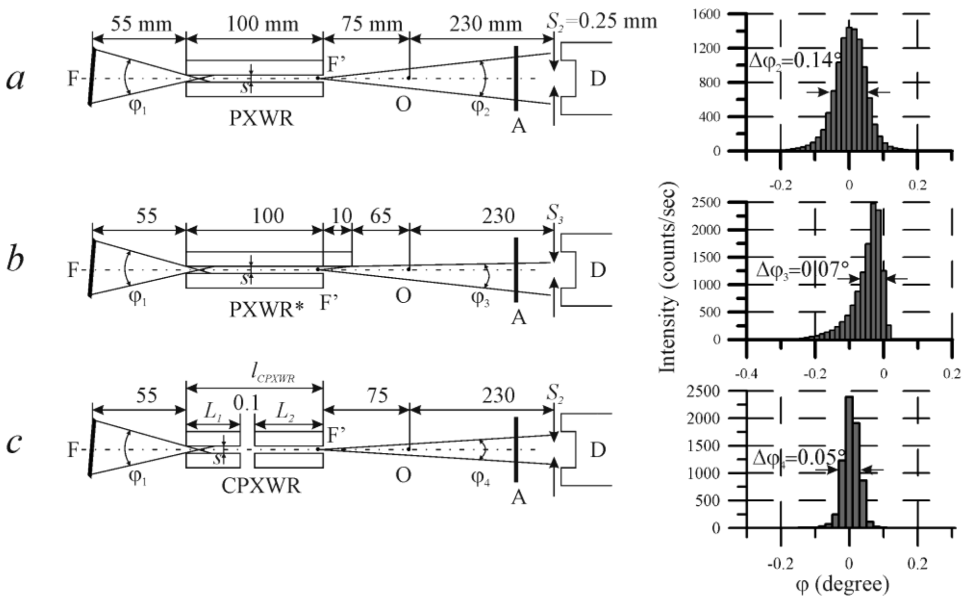

Figure 3. Schemes of X-ray quasimonochromatic beams formation by simplest PXWR, waveguide-resonator built on base (a) of nonequivalent length reflectors (b) and composite waveguide-resonator (c) and intensity spatial distributions in emergent beams of its devices.

X-ray photons flux is the sample of real statistical ensemble. Similar ensemble properties description is subject to the Liouville theorem, whereby the variation of one ensemble parameter must be accompanied by change of its other one. Integral intensity of CPXWR emergent beam does not undergo variation. At the same time, our X-ray precision diffraction measurements showed that its emergent beam is characterized by the degree monochromatization deterioration [13]. In the result, the model must characterize the function connection between X-ray beam angular divergence reduction $\Delta\varphi$ and its degree of radiation monochromatization $\Delta\lambda$.

The energy (E_p) and momentum (P_p) of single photon in the radiation flux generated by laboratory X-ray sources are defined by expressions [14]:

$$E_p = \hbar\omega = \frac{hc}{\lambda_0} = P_p c \tag{3}$$

$$P_p = \frac{E_p}{c} = \frac{h}{\lambda_0} \tag{4}$$

where h=2π, $\hbar$ is the Planck constant, ω is the radiation angular frequency and c is the light velocity in vacuum. Variation of these photon parameters can be obtained in the result of (3) and (4) expressions differentiation:

$$\Delta E_p = -\frac{hc}{\lambda_0^2}\Delta\lambda = \frac{P_p^2 c}{h}\Delta\lambda \tag{5}$$

$$\Delta P_p = -\frac{h}{\lambda_0^2}\Delta\lambda = -\frac{P_p}{\lambda_0}\Delta\lambda = \frac{P_p^2}{h}\Delta\lambda \tag{6}$$

Accordingly to hypothesis about the partial angular tunneling of X-ray flux in the gap between simplest waveguide-resonators one can believe that the tunneled flux part is characterized by $\vec{P}_1$ momentum been equal P_p. Vector of the momentum is directed at φ_1 angle to the composite waveguide-resonator axis. The emergent beam of CPXWR will be characterized by new momentum value $\vec{P}_2 = \vec{P}_p + \delta\vec{P}$ with new direction defined by φ_2 angle to the CPXWR axis. The experiment shows that $\varphi_1 > \varphi_2$. So, the flux angular divergence reduction is defined by expression:

$$\Delta\varphi = \varphi_1 - \varphi_2 \tag{7}$$

Owing to the total external reflection phenomenon of X-ray fluxes of material interfaces is characterized by very small angles it is possible to change function tangent on the function argument in the next form:

$$\Delta\varphi = (\varphi_1 - \varphi_2) \approx \frac{P_{y1}}{P_{x1}} - \frac{P_{y2}}{P_{x2}} \approx \frac{\Delta P_y}{P_p} \tag{8}$$

On the other hand, the scalar momentum value of photon can be presented on the conventional form:

$$P_p^2 = P_x^2 + P_y^2 \tag{9}$$

The momentum variation will be described by the next expression:

$$P_p \frac{\Delta P}{\Delta\varphi} = P_x \frac{\Delta P_x}{\Delta\varphi} + P_y \frac{\Delta P_y}{\Delta\varphi} \tag{10}$$

Owing to the tunneling effect is accompanied by chief variation of ΔP_y ordinate momentum component the expression (8) can be presented in the final form:

$$\Delta P_p = P_y \Delta\varphi = \Delta\varphi P_p \sin\varphi_1 \cong \Delta\varphi P_p \varphi_1 \tag{11}$$

Using the expression (6) we can get connection between X-ray flux angular divergence reduction and deterioration of its radiation monochromatism:

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$$\Delta\lambda = \varphi_1 \lambda_0 \Delta\varphi \quad (12)$$

Because of the initial degree monochromatization of X-ray flux is characterized by $\Delta\lambda_0$ the tunneling part of the flux will be described by increasing value of this parameter:

$$\Delta\lambda_2 = \Delta\lambda_0 + \varphi_1 \lambda_0 (\varphi_1 - \varphi_2) \quad (13)$$

In the result, it is clear that the composite waveguide-resonator decreases angular divergence in its emergent beam in comparison with X-ray beam formed by PXWR with simplest construction but it demonstrates worse monochromatism. Similar device can be used with success for X-ray fluorescence analysis but it is not acceptable for X-ray diffractometry.

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