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RESONATORS

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X-ray resonator with pear-shaped reflectors

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***Abstract*. An X-ray resonator design is proposed in which peculiar pear-shaped reflectors, which are grazing-incidence X-ray mirrors, serve as optical elements. Special features of this resonator are relatively high reflector efficiencies and the axial symmetry of the output radiation.**

Keywords: *grazing-incidence mirrors, conductivity coefficient.*

X-ray resonator design problems are discussed in the literature primarily in connection with X-ray laser development. X-ray resonators of several different types have been proposed to date [1 – 3].

The proposed resonator (Fig. 1) consists of two pear-shaped reflectors (*1*) and (*2*), whose surfaces are X-ray grazing-incidence mirrors. X-ray quanta propagate along these surfaces due to multiple reflections at small angles of incidence θ, which do not exceed the critical angle θ_{cr}: $\theta \leqslant \theta_{\text{cr}} = \sqrt{2\delta}$ (δ is the decrement of the refractive index of the reflector material). The reflectors are located along the common optical axis, with their openings (*3*) facing each other. One of the reflectors (*2*) has an opening (*4*) for the extraction of a part of radiation from the working substance. The working substance (*5*) of the X-ray laser is located between the resonator mirrors.

Each reflector of the resonator consists of two sections representing surfaces obtained by the revolution of two generating lines around the optical axis of the resonator (Fig. 2). The geometry of these surfaces may be different. The X-ray beam (*1*) incident on the input opening of the reflector is split into two beams: the interior (*2*) and exterior (*3*) ones. The interior beam propagates in the larger section of reflector (*4*) and is incident on the resonator 'cone' (*5*) to radially diverge along its inner surface, which transports X-ray quanta to the resonator slit (*6*), where they 'jump to' the outer-transportation mirror (*7*) and propagate along its surface to return to the same end of the working substance. For the X-ray quanta to propagate along the outer-transportation mirror surface and the returning mirror 'cone', these mirrors should evidently be concave in the section containing the optical resonator axis and convex in the section perpendicular to the direction of propagation. That is why the beam propagation will be unstable here. Owing to this instability, a part of the quanta will 'sheer off' and be lost, thereby reducing the resonator efficiency. The higher the resonator fabrication quality, the lower the fraction of X-ray quanta lost due to this instability.

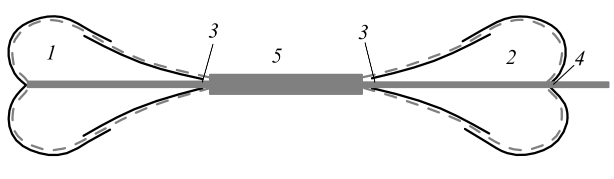

Figure 1. Scheme of the resonator with pear-shaped reflectors (the dashed lines show the trajectories of X-ray along the reflector surfaces): (*1*, *2*) pear-shaped reflectors; (*3*) input openings; (*4*) output opening; (*5*) working laser substance.

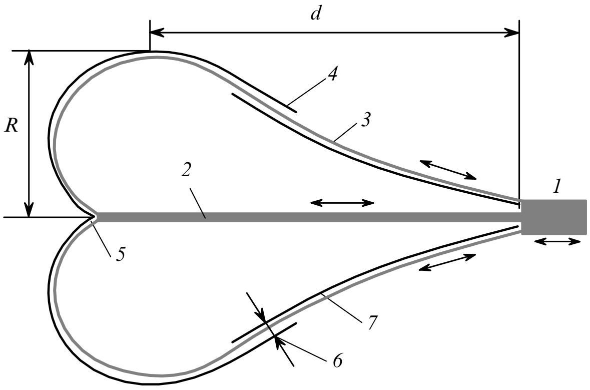

Figure 2. Scheme of the pear-shaped reflector: (*1*) X-ray beam; (*2*, *3*) interior and exterior radiation fluxes; (*4*) reflector section; (*5*) resonator 'cone'; (*6*) resonator slit; (*7*) outer-transportation mirror.

After the splitting of the incident beam, the exterior beam propagates evidently in the opposite direction the same path as the interior beam. The only difference between the two resonator reflectors is that one of them has an opening for the extraction of a part of radiation, which is made by 'cutting off' the vertex of the cone (Fig. 1). In essence, the idea of a pear-shaped reflector is the extension of the idea of a plane returning loop of a ring X-ray resonator, which was proposed in Ref. [3], to the three-dimensional case. Let us estimate the operation efficiency of the proposed resonator.

According to Refs [4, 5], the expression for the conductivity coefficient K of reflector surfaces is

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$$K \approx \exp(-\psi\gamma\delta^{-3/2}),$$

$$\delta = (2\pi)^{-1} N_{\mathrm{a}} r_{\mathrm{e}} \lambda^2 f_1, \; \gamma = (2\pi)^{-1} N_{\mathrm{a}} r_{\mathrm{e}} \lambda^2 f_2,$$

where ψ is the total angle of rotation in the reflectors related to the refractive index $n = 1 - \delta$ ($\delta \ll 0$ in the X-ray range); γ is the index absorption coefficient of the substance ($\gamma \ll \delta$); δ and γ are expressed in terms of atomic scattering factors f_1 and f_2 tabulated in Ref. [6]; N_{a} is the atomic number density; $r_{\mathrm{e}} = e^2 m^{-1} c^{-2}$ is the classical electron radius; and λ is the X-ray wavelength.

The total X-ray rotation angle ψ in the reflectors depends on the specific mirror geometry, lies between $360^\circ > \psi > 180^\circ$, and is determined by the expression

$$\psi = 180^\circ + 2\alpha,$$

where

$$\alpha = \arctan\frac{R - r}{d};$$

R is the reflector radius; r is the radius of the input opening of the reflector; d is the longitudinal distance between the entrance and the plane of the largest-area cross section of the reflector; and α is the deflection angle in the reflector. We assume that $R \gg r$ to arrive at a simplified expression for the deflection angle:

$$\alpha \approx \arctan\frac{R}{d}.$$

The ratio $(R - r)/d \approx R/d$ will be referred to as the reflector extension factor.

In reality it is possible to fabricate pear-shaped reflectors with a total rotation angle $\psi = 210^\circ - 270^\circ$, which is smaller than the rotation angle ($\psi = 360^\circ$) in ring resonators [2, 3], and therefore these reflectors should, unlike ring resonators, exhibit lower losses and form an axially symmetric X-ray beam. The conductivity coefficient K for reflectors takes different values for different materials and wavelengths as well as for surfaces of various quality. The conductivity coefficients estimated from experimental data [2] for several materials, wavelengths, and extension factors are presented in Table 1.

Table 1. Conductivity coefficients K for different materials, wavelengths, and angles of rotation.

Material	λ/Å	K	
		$\psi = 270^\circ$ ($R/d = 1$)	$\psi = 210^\circ$ ($R/d \approx 0.27$)
Ru	120	0.51	0.60
Ag	100 – 125	0.31	0.41
In	76	0.16	0.24

Stronger-extended reflectors possess a higher conductivity coefficient and form a beam with a smaller divergence. However, the X-ray quanta transit time is somewhat longer for them, which may be significant for X-ray lasers utilising short-lived plasma as the working material. For such conductivity coefficients, the resonator quality factor will be relatively low, though high enough to provide feedback in X-ray lasers.

Resonators involving grazing-incidence X-ray optics can be designed for a rather broad spectral range (from several tens to several hundred angstroms), which can be changed by selecting the material of the conducting mirror surface.

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