Ring cavity for grazing incidence mirror X-ray laser

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A simple cavity for the X-ray region is proposed. Its operation is based on grazing incidence X-ray optics. The cavity consists of two mirrors with coinciding optical axes. The cavity is open and axially symmetric. By the character of operation, the cavity is a ring one. The radiation in it is formed in opposite running waves: forward and backward beams. A condition for amplification in an X-ray laser with such a cavity is given.

Development of X-ray lasers demands creation of rather efficient laser cavities. In spite of the fact that X-ray optics yields to ordinary optics in the efficiency for X-ray lasers, several types of cavities were proposed, for example, cavities based on Bragg reflection from multilayer mirrors[1,2] and, in particular, a tunable cavity with such mirrors.[3] In the Nova X-ray laser, a cavity with one multilayer mirror having the reflection coefficient of about 15% (Refs. 4 and 5) was created. A ring cavity based on grazing incidence X-ray optics was proposed in Ref. 6.

A cavity proposed here consists of two mirrors arranged coaxially, that is, with coinciding optical axes (Figs. 1 and 2).

Mirror reflectivity is based on grazing incidence X-ray optics. X-rays in such mirrors propagate along the surface through multiple reflections at small angles θ smaller than the Brewster critical angle θ_c, at which total reflection occurs, $\theta_c \approx |\delta^{1/2}| > \theta$, where δ is the refractive index of the mirror substance. Such reflection angles are called grazing angles.

Mirrors themselves are surfaces of revolution of some generatrix around an axis coinciding with the mirror optical axis. The resulting mirror surface is axially symmetric. The generatrix may be a part of a circle of other curve oriented differently about the revolution axis. The possibility to vary the surface geometry to change X-ray properties points to some versatility of this cavity.

Grey color in Fig. 1*b* marks a mirror ring area with decreased reflectance, if X-ray quanta fall on the mirror in parallel with the optical axis. This mirror area does not work or work inefficiently; it will be called an *absorbing ring*. White ring areas on the external and internal sides of the *absorbing ring* are, respectively, *external* and *internal working areas*. Although in fact the boundary between the working and nonworking areas is somewhat fuzzy.

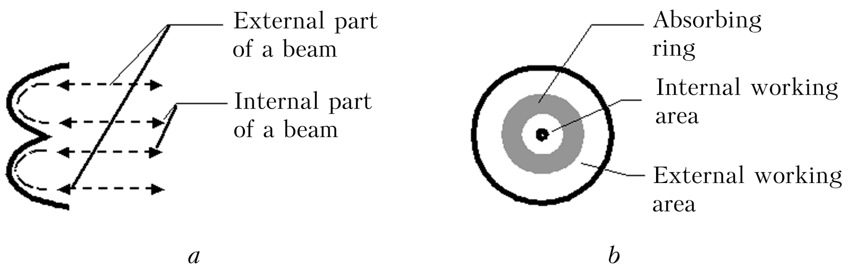

Fig. 1. Grazing incidence mirror of X-ray cavity. Side (*a*) and end (*b*) view.

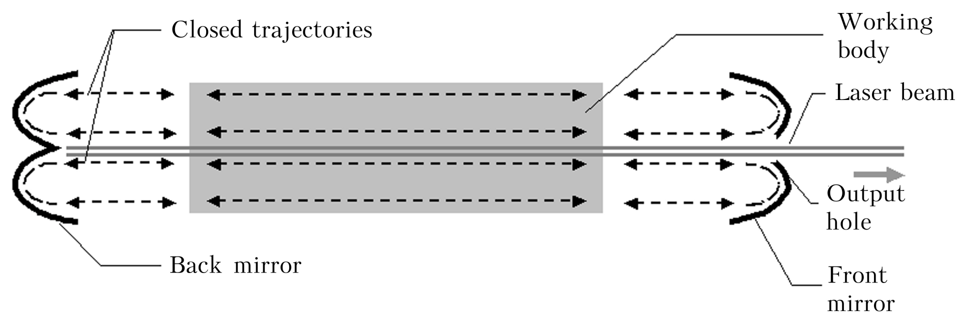

Fig. 2. Principal layout of ring cavity.

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Such a cavity is an axially symmetric open cavity. The closed trajectory of X-ray quanta inside the cavity indicates that it is a ring cavity. Induced radiation in this cavity is formed in two opposite running waves: *forward* and *backward beams*. Standing waves are not generated in this cavity.

As shown in Fig. 2, in the right mirror, a part of X-ray radiation of the internal part of the forward beam is turned off through the central hole, while the another is directed along the ring trajectory through the laser working body, where it is amplified.

Based on the quality of the mirror surface and the geometry of the reflecting surface, we can easily assume that the intensity distribution of X-ray radiation in a laser beam can have a radially inhomogeneous structure with minimum at the center and maximum closer to the external boundary of the beam, that is, the laser beam in the cross section may have a tubular structure, what is not always convenient. The output laser beam can be made more homogenous through corresponding correction of the left mirror, but this, in its turn, may increase the laser beam divergence.

In the other possible version of the cavity, a part of radiation from the backward wave is also turned off through the similar hole in the left mirror (symmetric version of the cavity). However, to improve the laser efficiency and homogeneity of the laser beam, it is desirable to direct the backward beam of the induced radiation into the forward beam.

In the third version, the backward wave is turned through 180° with a *return loop* – a capillary loop, in which X-ray quanta are turned through 180° due to multiple reflection from the capillary internal surface and directed into the same hole in the left mirror. The return loop was proposed in Ref. 6.

If the right mirror is replaced by a system of two mirrors, as shown in Fig. 3, then the possibility of using the backward wave is solved in the different way, where some its part leaves the cavity through a hole, while the rest part diverges radially over the mirror surface and turns through 180°. Quanta go along the mirror surface due to multiple reflection from the surface at grazing angles. After the turn, the X-ray quanta in the form of a beam are directed to the left mirror. This part of the beam provides for feedback in the laser. It will be called the *external* part, and the *internal* part is the part of the beam formed along the mirror optical axis. Just this beam forms the laser beam (see Fig. 2). At the second mirror, the beam is turned through 180° and directed to the central part of the mirror and then to the right mirror. Then the cycle is repeated.

At operation of the laser with this cavity, a situation is possible that only the internal part of the beam passes through the working body and underwent amplification (*single-pass mode*) or both parts (internal and external) of the beam are amplified, see Fig. 2 (*two-pass mode*). Stimulated emission of quanta occurs as they pass through the working body, and the longer is the distance passed by a quantum in the working body, the more efficient is amplification. Therefore, operation of the X-ray laser in the two-pass mode considerably improves the cavity efficiency.

The following equation for the laser beam intensity is fulfilled:

$$I = I_0 k R (1 - \beta_1 - \beta_2) \exp(qbl\sigma\Delta N). \qquad (1)$$

Here I is the beam intensity after termination of the whole cycle; I_0 is the initial beam intensity; $\Delta N = N_2 - \frac{g_2}{g_1} N_1 > 0$ is the laser level population inversion; N_1 and N_2 are the concentrations of emitting systems (for example, ions) being, respectively, at the upper and lower laser levels, and g_1 and g_2 are the weights of these levels. The coefficients q and b take the following values: $q = 1$ for the single-pass mode and $q = 2$ for the two-pass mode,

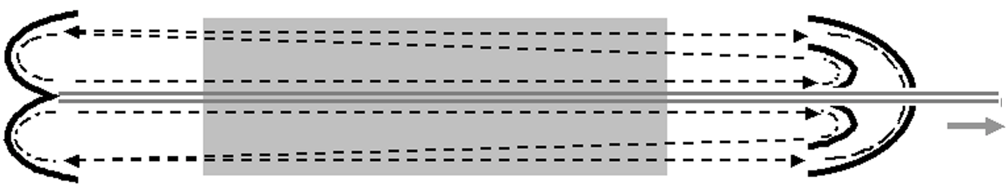

Fig. 3. Principal layout of ring cavity with matched forward and backward beams.

what can be easily seen by considering the directions of motion of X-ray quanta along the trajectories. In this cavity, the volume of the working body is larger than in the cavity shown in Fig. 2, what additionally increases its efficiency. Other designs of the cavity are possible, in which the backward beam either is not generated or is turned and directed into the forward beam.

Let us describe the cavity operation. The flux of X-ray quanta going out from the face end of the working body (see Fig. 2) falls on the right mirror, $b = 1$ for the cavity using only the forward beam for lasing (see Fig. 1), and $b = 2$ for the cavity using both the forward and backward beams (see Fig. 2); l is the length of the laser working body, which is assumed roughly equal for the both types of the cavity (see Figs. 1 and 2); $\sigma = (8\pi)^{-1}\nu^{-2}c^2 A_{21} g(\nu - \nu_0)$ is the induced radiation cross section, where ν and ν_0 are, respectively, the frequency and the resonance frequency of laser radiation, A_{21} is the probability of spontaneous transition between the laser levels, $g(\nu - \nu_0)$ is the line profile. In Eq. (1) β_1 and β_2 are the losses for scattering and absorption in the medium; k is the rest part of the X-ray beam in the cavity after output of the laser beam $(1 \geq k \geq 0)$; R is the conductance coefficient of the mirror surface[7]:

$$R = \exp(-\psi\gamma\delta^{-3/2}), \qquad (2)$$

where ψ is the rotation angle; δ is the refractive index of the mirror substance; γ is the absorption coefficient of the mirror substance, which is determined through atomic scattering factors f_1 and f_2 tabulated in Ref. 8:

$$\delta = (2\pi)^{-1} N_a r_e \lambda^2 f_1, \quad \gamma = (2\pi)^{-1} N_a r_e \lambda^2 f_2; \qquad (3)$$

N_a is the atom density; $r_e = e^2 m^{-1} c^{-2}$ is the classical electron radius; λ is the X-ray radiation wavelength (δ and γ are considered in detail in Ref. 9). For different substances and different wavelengths the value of R usually ranges from 0.1 to 0.4. The condition for laser operation is achievement of the critical population inversion ΔN_c, which can be easily found from Eqs. (1) and (2):

$$\Delta N_c = -\frac{\chi}{qbl\sigma} = \frac{8\pi\nu^2}{c^2 qblA_{21} g(\nu_0)} \times$$
$$\times \{360°\gamma\delta^{3/2} - \ln[k(1 - \beta_1 - \beta_2)]\}, \qquad (4)$$

where it is taken into account that the rotation angle $\psi = 360°$, that is, for one cycle; logarithmic loss in the cavity $\chi = 360°\gamma\delta^{-3/2} - \ln(k(1 - \beta_1 - \beta_2))$ is introduced and the line profile is taken at $\nu = \nu_0$.

Normal operation of the cavity is possible, when the lifetime of the population inversion in the working body τ is longer than or comparable with the period of one cycle $\tau_c = c^{-1}L \approx 3.3 \cdot 10^{-8}$ s, where L is the mean length of the path passed by quanta for every cycle. For estimation it was assumed $L \approx 10$ cm. In the case that the working body is laser plasma or plasma of high-current discharges, its lifetime is from 10^{-9} to 10^{-8} s. Therefore, the condition $\tau > \tau_c$ is fulfilled at the corresponding duration of pumping, which may be photopumping, recombination or combined pumping.

The proposed cavity operates in a rather wide region of X-ray radiation and this region can be changed by varying the material of the mirrors.

At two-pass mode of the cavity operation and the homogenous density of population inversion in the working body, the following feature is observed. At transition from the internal to the external part of the beam, the radiation density decreases, because the cross section of the internal beam s is less than the cross section of the external beam S. The cross sections of the internal and external beam parts can be taken equal to, respectively, the internal and external working areas of the mirrors. Vice versa, at the transition from the external part to the internal one, the beam density increases. Neglecting the loss at quanta transportation along the mirror surface and the loss for emission of the laser beam, the following relation for the density of the internal j_0 and external j_1 beams for the cavity mirrors is valid:

$$I_0 = Sj_1 = sj_0.$$

Because of the high radiation density in the internal part of the beam, its saturation is possible at sufficient amplification, when the population inversion is zero: $\Delta N = 0$. In this case, the amplification and absorption processes become balanced for the internal part of the beam and the medium clears up, while amplification in the external part of the beam is still possible because of its lower density.

The proposed principle makes possible development of various designs of X-ray cavities based on such mirrors. Such parameters as the number of mirrors, number of beam passes through the working body, presence and number of mirrors, which can be enclosed in one another, geometry of the mirror surface, mutual arrangement of mirror focuses, arrangement and number of holes for laser radiation output, and others can be varied.

The Q-factor and stability of cavities, as well as their different designs call for separate consideration.

This cavity, in contrast to that proposed in Ref. 6, is more compact and more practically feasible, and the laser beam formed in this cavity is radially symmetric.

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