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Possibility of protecting a mirror of a laser on the 4d – 4p transitions of nickel-like tantalum ions against spontaneous X-rays by means of a filter

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***Abstract*. The possibility of protecting a mirror of a laser on the 4d – 4p transitions of nickel-like tantalum ions against spontaneous X-rays by means of a carbon or potassium filter is considered. It is shown that such filters can transmit 75 % – 80 % of laser radiation at 44.83 Å, attenuating at least by half the intensity of radiation incident on the mirror in other spectral regions, which considerably suppresses the double-pass amplification.**

Keywords: *X-ray laser, multilayer mirror.*

1. Introduction

The improvement of the efficiency and other parameters of lasers on the 4d – 4p transitions of nickel-like Ta ions and heavier elements with the help of a mirror providing the double-pass amplification is of great practical interest. Such lasers can be used for studying the structure of living biological cells and plasma diagnostics in experiments on initiating thermonuclear microexplosions; however, the improvement of their parameters by elongating the active medium is complicated due to stringent requirements to pumping [1 – 6].

Unsuccessful experimental attempts to use multilayer mirrors for obtaining the double-pass amplification of radiation at the 44.83- Å 4d – 4p transition of nickel-like Ta ions were reported in papers [1 – 3]. In most experiments mirrors consisted of WC and C layers; also, mirrors consisting of W and C layers were used. The active medium of length $L_\text{m} = 3$ cm was pumped simultaneously over the entire length by exposing a Ta/lexane target to radiation at 0.53 μm focused to a line. The pump pulse FWHM was ~ 500 ps. The gain lifetime t_gain was estimated as 250 – 350 ps [1, 2]. Because t_gain was small, one of the conditions for obtaining a considerable amplification of reflected radiation was to mount a mirror at a distance of $b \leqslant 2$ cm from the active medium end. Experiments were performed for $b = 2$ and 6 cm. In the first case, the mirror was damaged so rapidly that the laser beam was not reflected after the first passage [1 – 3]. In the second case, the laser pulse was reflected after one passage without considerable amplification [1, 3].

The experiments were performed by using a protective filter mounted between the active medium and mirror and without this filter [1 – 3]. In the second case, the mirror was damaged by scattered pump radiation [2]. The filter consisted of a plastic and aluminium, transmitted approximately 75 % – 80 % of radiation at 44.83 Å and suppressed almost all pump radiation [2, 3]. With this filter for $b = 2$ cm, the mirror was damaged mainly by spontaneous X-rays emitted by the active medium [1 – 3].

We show in the present paper that the optimisation of the composition of the protective filter will provide the acceptable transmission of radiation at 44.83 Å and ensure at least twofold attenuation of spontaneous X-rays incident on the mirror in other spectral regions, which cause a rapid damage of the mirror, thereby suppressing the double-pass amplification. The data obtained in [1 – 3] suggest that this will provide the efficient double-pass amplification on the 4d – 4p transitions of nickel-like Ta ions.

2. Attenuation of spontaneous X-rays of the active medium by means of carbon, potassium, and aluminium filters

Consider the efficiency of protection of a mirror of a laser on the 4d – 4p transitions of nickel-like Ta ions with the help of carbon, potassium, and aluminium filters. The wavelength 44.83 Å is close to the wavelengths of local minima of photoionisation cross sections σ_C and σ_K of carbon and potassium atoms [7, 8], which allows the use of filters of thickness providing a considerable attenuation of spontaneous radiation in important spectral regions. The photoionisation cross section σ_Al of the aluminium atom does not have this feature [7, 8]. Aluminium is considered to demonstrate the importance of a proper choice of the filter material and analysis of data presented in [2, 3].

According to [3], when a filter is used and $b = 2$ cm, a rapid decrease in the reflectance of the WC/C mirror is caused by photons with energies $E < 1$ keV. Such photons are absorbed in the mirror at comparatively small distances, resulting in the nonuniform heating producing the nonuniform expansion of the mirror, which leads to a rapid loss of the mirror structure periodicity. This expansion could be partially caused by the transformation of amorphous carbon to graphite [3]. The damage of the mirror by photons of energy $E > 1$ keV occurred comparatively slowly and, there-

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fore, did not introduce a considerable contribution to the suppression of the double-pass amplification (see also [9] and section 3 of the present paper).

The attenuation of spontaneous emission of the active medium by the filter can be completely analysed for the range 30 Å $\leqslant \lambda \leqslant$ 100 Å (124 eV $\leqslant E \leqslant$ 413 eV) and situations when $L_{\mathrm{m}} \approx 1.7$ or 2.5 cm and the structure of a target and the pump radiation flux are approximately the same as in experiments described in papers [1–3]. This is explained by the fact that the shape of the spectrum of spontaneous emission emitted in the longitudinal direction by the active medium of the laser under study was presented in [2] for these values of λ and L_{m}. Of main interest is the value $L_{\mathrm{m}} = 2.5$ cm, which is considered below. The reason is that for $L_{\mathrm{m}} \approx 2.5 - 3$ cm, the slow enough damage of the mirror and small b, the amplification of radiation at 44.83 Å will be efficient both during the first and second passages through the active medium, whereas for $L_{\mathrm{m}} =$ 1.7 cm the amplification is small [1–3].

Let I_λ be the spectral density of spontaneous emission of the active medium of a laser on the 4d–4p transitions on nickel-like Ta ions, which is incident on the working surface of an unprotected mirror. The shape of the emission spectrum of the active medium can depend on time t; the data presented in paper [2] probably correspond to the intensity I_λ averaged over a certain time period. We assume below that effects related to the time dependence of the emission spectrum are insignificant.

It is convenient to describe I_λ analytically (for L_{m} =2.5 cm) by dividing the range 30 Å $\leqslant \lambda \leqslant$ 100 Å into five auxiliary ranges and represent I_λ corresponding to the ith range ($i = 1 - 5$) in the form

$$I_{\lambda i} \approx c_{\mathrm{g}}(b,t)[a_i + k_i\lambda + s_i^2(\lambda)], \tag{1}$$

where c_{g} is the total normalisation factor; λ is in ängstroms; and a_i, k_i, and s_i are fitting parameters determined by using data presented in [2] (Table 1).

Let $f(\lambda_1, \lambda_2)$ be the ratio of spontaneous emission intensities of the active medium in the spectral range $\lambda_1 \leqslant \lambda \leqslant \lambda_2$ incident on the mirror in the presence and absence of the filter, and the transmission coefficient of the filter is k_{f}. According to the definition, we have

$$f(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} I_\lambda(\lambda, b) k_{\mathrm{f}}(\lambda) \mathrm{d}\lambda \Big/ \int_{\lambda_1}^{\lambda_2} I_\lambda(\lambda, b) \mathrm{d}\lambda. \tag{2}$$

Table 1. Coefficients for the approximation of I_λ (30 Å $\leqslant \lambda \leqslant$ 100 Å, $L_{\mathrm{m}} = 2.5$ cm) from [2].

Range number	Range boundaries/Å	a_i	k_i	s_i
1	30–40	−38.9	2.5	−0.036
2	40–45	11.5	−0.2	0
3	45–55	7.0	−0.1	0
4	55–70	5.9	−0.1167	6.667×10^{-4}
5	70–100	4.355	−0.0655	2.5×10^{-4}

Consider the situation when the filter has the uniform thickness and the filter material is not noticeably ionised by scattered pump radiation and X-rays. In this case, we have

$$k_{\mathrm{f}}(\lambda) \approx \exp[-\mu_{\mathrm{f}}(\lambda) L_{\mathrm{f}}],$$

where μ_{f} is the attenuation coefficient of the filter at room temperature and L_{f} is the filter thickness. The value of L_{f} is chosen from the condition $k_{\mathrm{f}}(\lambda = 44.83$ Å$) \approx 0.75$ and 0.8 (see, for example, [2, 3]).

We assume that the densities of carbon, potassium, and aluminium filters are 2.25 (this value corresponds to graphite), 0.862, and 2.70 g cm^{-3}, respectively [10, 11]. The values of L_{f}, $f_1 = f$ ($\lambda_1 = 30$ Å, $\lambda_2 = 100$ Å), and $f_2 = f$ ($\lambda_1 \approx 31$ Å, $\lambda_2 \approx 62$ Å) corresponding to these densities and expressions (1) and (2) are presented in Table 2 (photoionisation cross sections are calculated according to [7]). The range 31 Å $\leqslant \lambda \leqslant$ 62 Å (200 eV $\leqslant E \leqslant$ 400 eV) is important because the authors of papers [2, 3] present the damage thresholds $S_1 \sim 0.1$ J cm^{-2} and $S_2 \sim$ 0.2–0.25 J cm^{-3} for WC/C and Cr$_3$C$_2$/C mirrors, respectively, for radiation in this spectral range.

In the range 300 eV $\leqslant E \leqslant$ 1 keV, cross sections σ_{C}, σ_{K}, and σ_{Al} decrease with increasing E [7, 8]. Carbon and potassium filters also considerably attenuate spontaneous emission at some values of $\lambda < 30$ Å ($E > 413$ eV). Table 2 presents photon energies $E_{1/3}$ and $E_{1/2}$ for these filters determined by the conditions $k_{\mathrm{f}} \leqslant 1/3$ for 413 eV $\leqslant E \leqslant E_{1/3}$ and $k_{\mathrm{f}} \leqslant 1/2$ for 413 eV $\leqslant E \leqslant E_{1/2}$.

According to [1], the irradiation intensity of the mirror in the range 500 eV $\leqslant E \leqslant$ 1 keV in experiments without the filter is approximately twice as large as that in the range 40 eV $\leqslant E \leqslant$ 500 eV. The attenuation of radiation by all filters under study in some parts of the range 500 eV $\leqslant E \leqslant$ 1 keV is weak (see the value of k_{f} for $E = 1$ keV in Table 2 and papers [7, 8]). Nevertheless, we can assume that, when carbon or potassium filters are used, photons in the range 500 eV $< E \leqslant$ 1 keV will not damage rapidly the mirror because the nonuniformity of its heating by such photons is comparatively small (see section 3) and all the values of $E_{1/2}$ exceed 500 eV (Table 2).

3. Nonuniformity of the temperature of a WC/C mirror

The nonuniformity of the temperature T_{m} of a mirror and of its thermal expansion produced upon irradiation by X-rays is determined by the intensity and shape of the emission spectrum, the characteristic absorption lengths l_{abs}

Table 2. Parameters of carbon, potassium and aluminium filters.

k_{f} ($\lambda = 44.83$ Å)	Filter material	L_{f}/Å	f_1	f_2	$E_{1/3}$/eV	$E_{1/2}$/eV	k_{f} ($E = 1$ keV)
0.75	C	5160	0.29	0.27	582	691	0.78
0.75	K	5810	0.41	0.39	503	611	0.82
0.75	Al	376	0.69	0.77	–	–	0.99
0.8	C	4000	0.34	0.31	528	629	0.82
0.8	K	4510	0.48	0.45	451	550	0.85
0.8	Al	292	0.75	0.81	–	–	0.99

of photons, the characteristic paths of photo- and Auger-electrons, the heat conduction and time.

Consider the action of X-rays on a mirror consisting of carbon layers of thickness $l_{\rm C} \approx 14.5$ Å and WC layers of thickness $l_{\rm WC} \approx 8$ Å [3]. It can be shown that

$$l_{\rm abs}(E) \approx \frac{l_{\rm C} + l_{\rm WC}}{\sigma_{\rm C}(E) n_{\rm C} l_{\rm C} + [\sigma_{\rm C}(E) + \sigma_{\rm W}(E)] n'_{\rm C} l_{\rm WC}}, \qquad (3)$$

where $n_{\rm C}$ and $n'_{\rm C}$ are the concentrations of carbon atoms in C and WC layers; $\sigma_{\rm W}$ is the photoionisation cross section of a tungsten atom (the case of $l_{\rm abs} \gg l_{\rm C} + l_{\rm WC}$ is considered).

Let us assume that the C layer density is 2.25 g cm^{-3} (the calculation of $l_{\rm abs}$ can be performed by neglecting the difference between the density of amorphous carbon and the maximum graphite density) and the WC layer density is 15.7 g cm^{-3} [12]. The lengths $l_{\rm abs}$ calculated from expression (3) for several photon energies for the specified layer densities and values of $\sigma_{\rm C}$ from [7] and $\sigma_{\rm W}$ from [8] are presented in Table 3 ($E \approx 277$ eV is the energy of a photon with $\lambda \approx 44.83$ Å).

Table 3. Absorption of X-rays and thermal diffusion in a WC/C mirror.

E/eV	$l_{\rm abs}$/Å	$\tau_{\rm s}\ (\Delta L = l_{\rm abs})$/ps
100	840	44
200	710	31
277	800	40
300	470	14
400	800	40
500	1110	77
600	1530	150
700	2060	270
1000	4260	1100

It is convenient to analyse the deceleration of electrons by considering their characteristic path lengths $l^{\rm e}_{\rm C}$ and $l^{\rm e}_{\rm WC}$ in carbon and WC, respectively. Let us estimate $l^{\rm e}_{\rm C}$ for the initial kinetic electron energy 100 eV $\leqslant \varepsilon \leqslant$ 1 keV as

$$l^{\rm e}_{\rm C} \approx \varepsilon \bigg/ \left|\frac{{\rm d}\varepsilon}{{\rm d}x}\right|_{\rm C}, \qquad (4)$$

where

$$\left|\frac{{\rm d}\varepsilon}{{\rm d}x}\right|_{\rm C} \approx \frac{8\pi n_{\rm C} e^4}{\varepsilon} \ln\left(\frac{\varepsilon}{15\ {\rm eV}}\right) \qquad (5)$$

is the loss of the kinetic electron energy per unit path in carbon and e is the electron charge. Expression (5) takes into account the ionisation of only carbon levels with the principal quantum number $n = 2$, the average ionisation potential of these levels being assumed equal to 15 eV (see, for example, [7, 13]).

It follows from expressions (3) – (5) that $l^{\rm e}_{\rm C} \ll l_{\rm abs}$ for 100 eV $\leqslant \varepsilon \leqslant$ 1 keV and $E > \varepsilon$. For example, $l^{\rm e}_{\rm C} \approx 50$ and 400 Å for $\varepsilon = 300$ and 1 keV, respectively, whereas $l_{\rm abs} \geqslant$ 470 Å for $E \geqslant 300$ eV and $l_{\rm abs} \approx 4300$ Å for $E = 1$ keV (see Table 3). It can be shown that a similar relation also takes place for $l^{\rm e}_{\rm WC}$. Thus, characteristic distances at which the energy of X-rays is transferred to the mirror material are determined by the absorption of photons and are almost independent of $l^{\rm e}_{\rm C}$ and $l^{\rm e}_{\rm WC}$.

Let us estimate the importance of heat transfer due to heat conduction. We assume that the heat conductivity of C layers considerably exceeds the heat conductivity of WC layers $\varkappa_{\rm WC} \approx 0.35$ W cm^{-1} K^{-1} (this is the heat conduction of a volume WC [12]). According to this assumption, the effective heat conductivity along the normal to the mirror surface is $\varkappa_{\rm m} \approx \varkappa_{\rm WC}(l_{\rm C} + l_{\rm WC})/l_{\rm WC} \approx 0.98$ W cm^{-1} K^{-1}, while the effective thermal diffusivity $\chi_{\rm m}$ equal to the ratio of $\varkappa_{\rm m}$ to the average heat capacity of the mirror unit volume (see, for example, [14]) is ~ 0.4 cm^2 s^{-1} (here, we used the heat capacity of materials from [10, 15], the heat capacity of WC corresponds to $T_{\rm m} = 1000\,^{\circ}$C [1, 3, 15]. The characteristic time $\tau_{\rm s}$ of smoothing the nonuniformity of $T_{\rm m}$ with a spatial scale ΔL due to heat conduction can be estimated as $\tau_{\rm s} \approx \Delta L^2/(4\chi)$ [14].

The characteristic variation time $\tau_{\rm m}$ of local parameters of the active medium of a laser on the 4d – 4p transitions of nickel-like Ta ions in experiments [1 – 3] was of the order of 10^{-10} s. For example, data presented in [1] correspond to approximately a linear increase in the factor $c_{\rm g}$ with time from zero to a value close to maximal during ~ 250 ps and a small change in $c_{\rm g}$ during following 250 ps up to the moment corresponding to the maximum gain (see also estimates of $t_{\rm gain}$ presented above). Thus, the smoothing of the nonuniformity of mirror heating by photons with energies ~ 1 keV and above due to heat conduction was virtually insignificant; however, at lower values of E, for example for $E \leqslant 500$ eV, this process was quite important (see Table 3). Note that the condition $\tau_{\rm s} \approx 250$ ps for $\Delta L = l_{\rm abs}$ corresponds to $l_{\rm abs} \approx 2000$ Å and $E \approx 690$ эВ.

In experiments [5, 6], lasers on the 4d – 4p transitions of nickel-like Ta ions were pumped by $\sim$ 100-ps laser pulses. In this case, $\tau_{\rm m}$ is probably ~ 100 ps or smaller. The condition $\tau_{\rm s} \approx 100$ ps for $\Delta L = l_{\rm abs}$ corresponds to $l_{\rm abs} \approx 1260$ Å and $E \approx 540$ eV.

At the wavelengths for which $\tau_{\rm s}\,(\Delta L = l_{\rm abs}) \gg \tau_{\rm m}$ in the presence of a filter, the contribution of radiation in the range from a wavelength λ_0 to $\lambda_0 + \Delta\lambda$ to the nonuniformity of mirror heating and thereby to the suppression of the double-pass amplification is determined by the parameter $I_{\lambda}(\lambda_0) k_{\rm f} \Delta\lambda / l^2_{\rm abs}(\lambda_0)$; in the absence of the filter this contribution is determined by the parameter $I_{\lambda}(\lambda_0)\Delta\lambda / l^2_{\rm abs}(\lambda_0)$.

4. Example of requirements to a decrease in the flux density of spontaneous X-rays and possible filter designs

Let $F_{\rm tot}$ be the flux density of X-rays incident on an unprotected mirror during the entire irradiation time. This quantity is the sum of contributions from spontaneous and stimulated radiation $F^{\rm sp}_{\rm tot}$ and $F_{\rm las}$, respectively. The flux density of spontaneous X-rays incident on a mirror before the incidence of the reflected laser pulse is denoted by $F^{\rm sp}_{\rm ref}$.

In experiments described in papers [1 – 3], the relation

$$F^{\rm sp}_{\rm ref} \approx (0.4 - 0.5) F^{\rm sp}_{\rm tot} \qquad (6)$$

was fulfilled for an unprotected mirror. According to [2] for $L_{\rm m} = 3$ cm and $b = 2$ cm we have $F_{\rm tot} \approx 0.4$ J cm^{-2} and $F_{\rm las} \approx 0.05$ J cm^{-2}, which corresponds to $F^{\rm sp}_{\rm tot} \approx$ 0.35 J cm^{-2}. In [3], the values $F_{\rm tot} \approx 0.2$ J cm^{-2} and $F_{\rm las} \approx 0.03$ J cm^{-2} are presented for the same conditions, which correspond to $F^{\rm sp}_{\rm tot} \approx 0.17$ J cm^{-2}. These data, the value of the threshold S_1 presented above, estimates by (6) and values presented in Tables 2 and 3 suggest that in situations when $L_m \approx 2.5$ cm, $b \approx 2$ cm, and the target structure and the pump flux are approximately the same as in experiments [1–3], a carbon or potassium filter will prevent the damage of the WC/C mirror by spontaneous X-rays before the incidence of the reflected laser pulse. Such filters can be also used to protect Cr_3C_2/C mirrors; however, this question requires special studies.

A carbon filter can consist either of pure carbon, for example, graphite supported, if necessary, by a net or another construction element [4] or of a carbon layer located between two plastic layers, for example polyethylene [16]. It seems that a graphite layer of thickness of a few thousands ängstrom (see Table 2) will also protect the mirror against scattered pump radiation. If necessary, a filter can be used which consists of a $\sim$ 1000-Å-thick carbon layer, a $\sim$ 100-Å-thick potassium layer reflecting scattered pump radiation and of one or two plastic layers.

It is expedient to place a potassium layer of thickness of a few thousands ängstrom (see Table 2) between plastic layers. In any case, carbon filters will be more efficient.

Note that the filter used in experiments [3] consisted of a 240-Å-thick aluminium layer placed between lexane layers of thickness 2400 and 1000 Å. This filter did not provide the protection of the mirror against X-rays (see Table 2).

5. Conclusions

A carbon filter can be efficiently and simply used to protect the WC/C mirror of a laser on the 4d–4p transition of nickel-like tantalum ions against spontaneous X-rays. The complete optimisation of the design of a double-pass laser on these transitions can involve the analysis of the expediency of using these filters for protecting other mirrors and also analysis of the efficiency of filters containing plastic layers of comparatively large thickness, corresponding to the minimal admissible values of k_f ($\lambda = 44.83$ Å) (see, for example, [1–3, 16].

The efficient protection of mirrors against spontaneous X-rays with the help of a filter is probably possible for other X-ray lasers as well. The use of the filter can be supplemented by other methods for mirror protecting, in particular, by using a travelling pump wave propagating toward the mirror at the speed of light [17] or by cooling preliminarily the mirror down to the liquid nitrogen or helium temperature to prevent the transformation of amorphous carbon to graphite. A decrease in b achieved by combining various methods for mirror protecting will increase the fraction of reflected laser radiation incident on the main amplifying region of the active medium (see also [3, 18]).

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