OPTICS. QUANTUM ELECTRONICS. HOLOGRAPHY

DEVELOPMENT AND APPLICATION OF RESONATOR MIRRORS WITH DISPLACED SPECTRAL CHARACTERISTICS FOR SELECTION OF LASER TRANSITIONS

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As elements of dispersive resonators, we offer to use the interference mirrors with displaced spectral characteristics (MDSC). For an estimation of the selection properties of MDSC, the parameter of selectivity which is defined by basic constructive performances of the used mirrors is introduced. Constructions of the suggested mirrors are optimized from the point of view of the used film-forming materials. The results of experiments confirm the efficiency of the selection of laser transitions with MDSC.

The solution of modern problems of metrology, laser medicine, and telecommunications is connected with the fabrication of powerful highly monochromatic lasers. Gas discharge lasers with active media Ar^+, Kr^+, and He—Se^+ work mainly in the visual and adjoining areas of a spectrum. The considerable level of power successfully combines with high spatial homogeneity of the output radiation in this type of lasers. Spectral characteristics of the output radiation are very important at the fabrication of lasers for the specified application. In this respect, serial models LGN-106, LGN-402, LGN-406, and LGN-502 filled up with Ar^+ whose output power amounts up to 5 W are interesting to be investigated. Such lasers do not belong to a highly monochromatic type, because their radiation represents the assemblage of discrete lines in the blue-green range of a spectrum. The argon laser model LGN-503 is equipped with an intraresonator autocollimation prism and allows developing the selection of separate lines of generation. Thermooptical effects which appear as a result of the volume absorption of powerful radiation by a material of a prism, and the dependence of the refractive index and a refraction angle on temperature restrict a level of stability of performances of output radiation for the given type of lasers. A relatively high level of intraresonator energy losses (more than 1 %) gives rise to a change of power (up to 1 W), and the generation is missing at all on some feeble laser transitions (Ar^+) of the visual range.

Thus, the search for new approaches to the design of powerful Ar^+-lasers which radiate on separate lines, is actual today. One of the most important directions in this aspect could be the application of dispersion resonators which use the selection properties of mirrors. The modern technological level of a vacuum spraying of interference coatings allows one to create mirrors with a level of the dissipative losses which do not exceed 0.3 % [1]. At rather low levels of the unsaturated amplification on feeble laser transitions in Ar^+ (1—5 % m^{-1}), such a decrease of intraresonator losses becomes quite essential.

Selective properties of the interference mirrors are defined by the character of their reflective spectrum. Let us consider the quarter-wave multilayer structure

$$S_0\ A_1,\ A_2, ..., A_k, \tag{1}$$

where S_0 — a substrate with refractive index n_s; A_1, A_2, ..., A_k — thin layers with refractive indices $n_1, n_2 ... n_k$. In the case of two-component mirror, whose spectral characteristics are shown in Fig.1, the thin-film structure looks as

$$S_0B, H, B, H, B, H, B, H, B, H, B, , H, B, H, B, H, B$$

or

$$S_0(B, H)_8B, \tag{2}$$

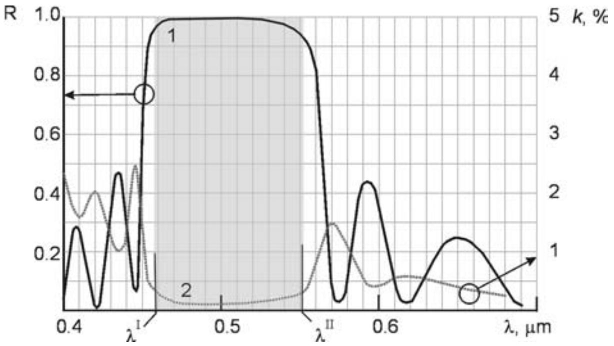

Fig. 1. Reflection (*1*) and absorption (*2*) spectra of a 21-layer two-component interference mirror produced by deposition of thin layers ZrO_2 and SiO_2 on the optical quartz substrate

where S_0 — optical quartz, B—ZrO_2, H—SiO_2. Optical thickness of the layers equals 0.5/4 μm.

As follows from Fig. 1, the reflection spectrum of the quarter-wave two-component structure has three specific ranges which are the long-wave and short-wave ranges of low reflection power with periodically changing coefficient R and the central range of high reflection (plateau). The highest value of the coefficient R (plateau) at the wavelength λ_0 =0.5 μm [2] is

$$R = \left[\frac{1 - \frac{n_B}{n_S}\frac{n_B}{n_0}\left(\frac{n_B}{n_H}\right)^{K-1}}{1 + \frac{n_B}{n_S}\frac{n_B}{n_0}\left(\frac{n_B}{n_H}\right)^{K-1}}\right]^2, \tag{3}$$

where n_0 — the refractive index of the external medium.

It is important to determine the wavelengths which correspond to the long-wave and short-wave edges of the high reflective range of the multilayer coating. Using the matrix method of the theory of layered structures, it was shown in [3] that the long-wave λ^{II} and short-wave λ^I edges of reflection of two-component quarter-wave interference mirrors depend only on the ratio of reflective indices of the coating components and are defined by

$$\lambda^I = \frac{\pi}{2}\frac{\lambda_0}{\pi - \mathrm{arctg}\left(\frac{2(n_B n_H)^{1/2}}{n_B - n_H}\right)}, \tag{4}$$

$$\lambda^{II} = \frac{\pi}{2}\frac{\lambda_0}{\mathrm{arctg}\left(\frac{2(n_B n_H)^{1/2}}{n_B - n_H}\right)}. \tag{5}$$

T a b l e 1. Calculated values λ^I, λ^{II}, and S for various two-component mirror coatings

N	Materials of the layers	n_B	n_H	λ^I, μm	λ^{II}, μm	S
1	ZnS—MgF_2	2.3	1.38	0.431	0.596	3.11
2	HfO_2—SiO_2	2.0	1.45	0.453	0.556	4.91
3	ZrO_2—SiO_2	1.95	1.45	0.457	0.551	5.32

For an estimation of the selective properties of the interference mirrors which are produced of various materials, we can introduce the selectivity parameter

$$S = \frac{\lambda^I \lambda^{II}}{\lambda_0(\lambda^{II} - \lambda^I)}. \tag{6}$$

With regard for (4) and (5), we can write

$$S = \frac{\pi}{2}\left(\pi - 2\mathrm{arctg}(\frac{2\,(n_B n_H)^{1/2}}{n_B - n_H}\right)^{-1}. \tag{7}$$

Values of the selectivity parameter and the edges of the high reflective range for various pairs of materials are given in Table 1.

It follows from Table 1 that selection properties of the mirrors, which are produced with application of the classical film-forming materials, are insufficient for the generation of spectrally separated laser transitions in the active medium of Ar^+. For the selection of separated laser transitions, it is necessary to use the mirrors of optical resonators which provide a high Q-quality in a comparatively narrow (5÷10 nm) spectral band. In this case, the selectivity parameter S must remain in the range 10÷50. In accordance with (7), we can improve the given parameter by fitting the coating components with close values of the refractive indices. In this case, high reflectance is provided by increasing the total amount of the layers, which, in turn, increases losses in the mirrors. Such coatings are short-lived and have low performance properties [1].

It follows from the stationary generation requirement for a two-mirror optical resonator [4],

$$R_1\,(\lambda)\,R_2\,(\lambda)\exp(2G_0 l) = 1, \tag{8}$$

where $R_1(\lambda)$ and $R_2(\lambda)$ — spectral reflection coefficients of the mirrors; G_0 — coefficient of unsaturated amplification, and l — length of the active medium, that the selective properties of the resonator are determined eventually by the product of the spectral reflection coefficients of the mirrors. The lowest selective properties are revealed by resonators with interference mirrors, which have coincident peaks of reflection. Selective properties of a resonator increase if one uses MDSC. In this case,

$$S = \frac{\pi}{2}\frac{\lambda_{01}\lambda_{02}}{\lambda_{00}}\left(\lambda_{01}\left(\pi - \mathrm{arctg}\frac{2(n_B n_H)^{1/2}}{n_B - n_H}\right) - \right.$$

$$\left. -\lambda_{02}\mathrm{arctg}\frac{2(n_B n_H)^{1/2}}{n_B - n_H}\right)^{-1}, \tag{9}$$

where λ_{00} — wavelength of the separated transition; λ_{01} and λ_{02} — wavelengths which correspond to the maximum of reflectance of the "outcoupling" and "nontransmitting" mirrors. From (4) and (5), we obtain

$$\lambda_{01} = \frac{2}{\pi}\lambda_k \left(\pi - \mathrm{arctg}\frac{2(n_\mathrm{B} n_\mathrm{H})^{1/2}}{n_\mathrm{B} - n_\mathrm{H}}\right), \tag{10}$$

$$\lambda_{02} = \frac{2}{\pi}\lambda_g \left(\mathrm{arctg}\frac{2(n_\mathrm{B} n_\mathrm{H})^{1/2}}{n_\mathrm{B} - n_\mathrm{H}}\right), \tag{11}$$

where λ_g and λ_k — wavelengths of the discriminated long-wave and short-wave transitions which are adjacent to the separated transition. By using MDSC, we can select such values of wavelengths λ_{01} and λ_{02} that, into the range of high values of the product of spectral reflection coefficients, only that transition hits, which must be separated. If one of the adjacent transitions is situated outside of the high reflective range, then one of MDSC of the optical resonator must be of the same size as a separated transition wavelength.

Efficiency of MDSC depends on losses which they introduce in the resonator. The main type of losses in the mirrors of Ar^+-lasers is absorption losses which are determined by absorption of the laser emission on mirror's coating materials. Application of the selective resonators with MDSC gives rise to increasing this parameter, since operating points on the spectral curve are off-center of the absorption curve (Fig. 1). Therefore, the important point is the selection of materials which may be used in the production of the interference coatings of MDSC.

Influence of the absorption parameter is more essential for separating the short-wave transitions. Hence, the absorption losses we study in MDSC can be used in the resonators of Ar^+-lasers for the separation of the transition with λ=0.4545 μm. According to (10) and (11), the thin-film structures of corresponding optical resonator mirrors must be such as

$$\mathrm{S}_0(\mathrm{B},\mathrm{H})_{(K_1-1)/2},\mathrm{B} \tag{12}$$

and

$$\mathrm{S}_0(\mathrm{B},\mathrm{H})_{(K_2-1)/2},\mathrm{B}, \tag{13}$$

where S_0 — optical quartz; K_1 and K_2 — numbers of the layers in the case of the outcoupling and nontransmitting mirrors, respectively. Synthesis parameters K_1 and K_2 are determined by the requirement of optimum reflection on the given transition. They were obtained from the requirement of minimum of the valuation function

$$M = \sqrt{(D_i^2 - R_1^2(\lambda_i)\, R_2^2(\lambda_i)},\tag{14}$$

where D_i — required value of the product of the reflection coefficients of the mirrors for wavelength $\lambda_i, R_1(\lambda_i)$ and $R_1(\lambda_i)$ — obtained reflection coefficients of the resonator mirrors for this wavelength.

For the outcoupling mirror of an optical resonator, $D_i = \left(1 - \sqrt{2G_{0i}\beta} + \beta\right) 0.997$, where G_{0i} — coefficient of unsaturated amplification of a separated laser transition; β — total level of intraresonator losses ($\beta \approx 0.3$). For the nontransmitting mirror, D_{0i}=0.995.

We had used the method of nonlinear programming [5] for solving system (12) and (13) for K_1 and K_2. Their values obtained as a result of synthesis for the laser transition (Ar^+) at λ=0.4545 μm and absorption losses depending on chosen film-forming pairs of materials with the optical quartz glass substrate are shown in Table 2.

Optical constants of film-forming materials and their dispersion relations were taken from [6, 7]. As follows from the given data, from the point of view of minimal losses, the most suitable combinations of materials for producing MDSC are $\mathrm{HfO_2}$—$\mathrm{SiO_2}$ and $\mathrm{ZrO_2}$—$\mathrm{SiO_2}$. Absorption losses in such materials do not exceed the similar parameter for traditional selectors. In the visible spectrum, the chosen film-forming materials are characterized by normal dispersion and a sharper steepness of dispersion for shorter waves. For reducing the total absorption losses, it is necessary to produce nontransmitting MDSC with displacement to the long-wave range.

Spectral dependences of reflection power of the outcoupling and nontransmitting mirrors and the spectrum of the product of their reflective coefficients are shown in Fig. 2. We can see that this spectral curve is narrow and the separated transition belongs to its high-value range, whereas unnecessary transitions do not. Hence, we can conclude that our approach to the construction of selective resonators with MDSC is

Table 2. Calculated synthesis parameters and absorption losses κ of mirrors, such as (12) and (13), for different materials of thin layers for the transition at $\lambda = 0.4545$ μm

N	Materials of the layers	λ_{01}, μm	λ_{02}, μm	S	K_1	K_2	κ, %
1	ZnS—$\mathrm{MgF_2}$	0.391	0.510	21	11	23	6.40
2	$\mathrm{HfO_2}$—$\mathrm{SiO_2}$	0.412	0.481	21	23	31	0.25
3	$\mathrm{ZrO_2}$—$\mathrm{SiO_2}$	0.410	0.483	21	23	31	0.88

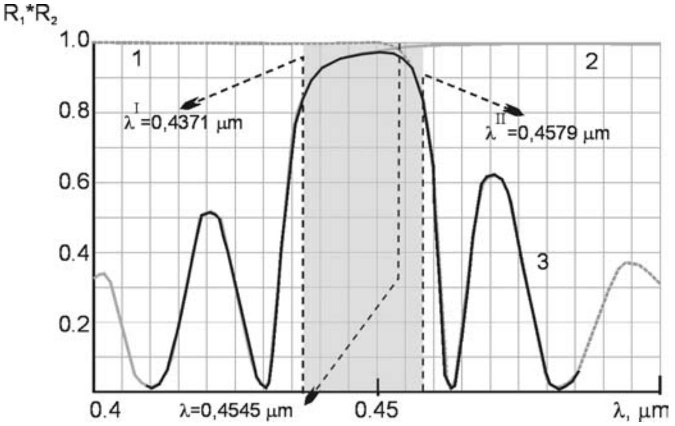

Fig. 2. Spectral dependence of the product of reflective coefficients of the mirror with thin-film structure 3 from Table 2. (*1* — reflective spectra of the nontransmitting mirror; *2* — reflective spectra of the outcoupling mirror; *3* — product of reflective coefficients)

correct. In Table 3, the obtained data on the MDSC synthesis of the optical resonators of Ar^+-lasers for a chain of quantum transitions are shown. One combination of ZrO_2—SiO_2 was in use.

Samples of MDSC were created by the vacuum deposition method with application of a facility of the type URMZ.273.060. Technological conditions and transitions corresponded to the typical technological process for refractory oxides ZrO_2—SiO_2 [1]. Transmission coefficients were checked on a SF-46 spectrophotometer and absorption losses were controlled by using a stand of interference calorimetry [8]. The determined total values of dissipative losses of the synthesized MDSC in the range of separated transitions did not exceed 0.6 %. Wavelengths of output radiation were measured by using a setup on the basis of a monochromator DMR-4.

Table 3. Characteristics of MDSC for the selection of transitions in the visible spectrum of an argon laser with $ZrO_2 - SiO_2$ layers

N	Wavelength of working transition, μm	λ^I, μm	λ^{II}, μm	λ_{01}, μm	λ_{02}, μm	K_1	K_2
1	0.5287	0.5145	—	0.5287	0.5682	23	31
2	0.5145	0.5017	0.5287	0.4734	0.5540	19	31
3	0.5017	0.4965	0.5145	0.4607	0.5483	23	31
4	0.4965	0.4880	0.5017	0.4493	0.5389	23	31
5	0.4880	0.4765	0.4965	0.4446	0.5262	19	31
6	0.4665	0.4658	0.4880	04370	05144	23	31
7	0.4658	0.4579	0.4765	0.4267	0.5057	32	31
8	0.4579	0.4545	0.4658	0.4171	0.5019	23	31
9	0.4545	0.4371	0.4579	0.4100	0.4827	23	31
10	0.4371	—	0.4545	0.4070	0.4545	23	31

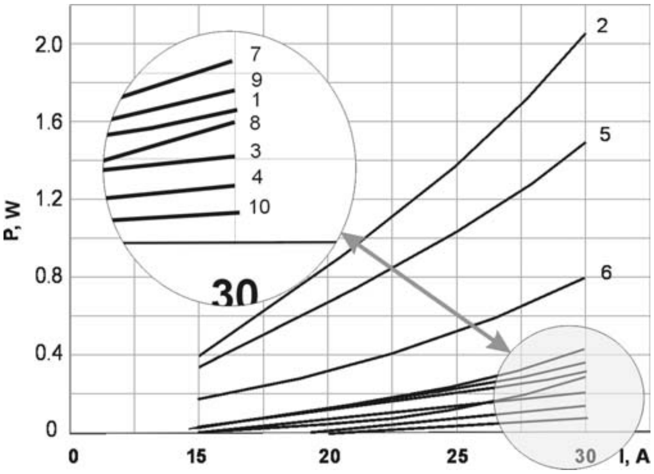

Fig. 3. Power-current dependences of selective transitions in an Ar^+-laser: *1* — 0.5287 μm; *2* — 0.5145, *3* — 0.5017, *4* — 0.4965, *5* — 0.4880, *6* — 0.4765, *7* — 0.4658, *8* — 0.4579, *9* — 0.4545, *10* — 0.4371

The efficiency researching of the received MDSC was done by using soldered active argon elements which were pressurized with Brewster windows. The length of discharge spacing equaled 500 mm, the diameter — 2.5 mm.

Using a solenoid with active element which generates a discharge current of 25A and the intensity of longitudinal magnetic field of 9 kOe, the selective generation on eleven visible laser transitions of Ar^+ was done. For the first time, the dependences of output radiation power for such transitions on the discharge current under low intraresonator losses conditions were investigated. Such dependences in the range 10—30 A on each generation line confirm the correspondence of the energy characteristics of the laser under study to the law of similarity

$$\frac{P}{V} = 10^{-5} j^2, \tag{15}$$

where P/V — volumetric density of generation power; j — discharge current density.

It is necessary to note that our approach to producing the highly monochromatic lasers with application of MDSC can be successfully applied for the development of other lasers with active media, which have many close laser transitions. We mean lasers with the filling with Kr^+, He—Se^+, He—Ne, etc. A low-loss level of such lasers allows improving the main characteristics of output radiation. It is important that the elimination of expensive selectors results to a reduction of prices in the serial production of lasers.

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РОЗРОБКА І ВИКОРИСТАННЯ РЕЗОНАТОРНИХ ДЗЕРКАЛ ЗІ ЗМІЩЕНИМИ СПЕКТРАЛЬНИМИ ХАРАКТЕРИСТИКАМИ ДЛЯ СЕЛЕКЦІЇ ЛАЗЕРНИХ ПЕРЕХОДІВ

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Резюме

Запропоновано як елементи дисперсійних резонаторів використовувати інтерференційні дзеркала зі зміщеними спектральними характеристиками (ДЗСХ). Для оцінки селективних властивостей ДЗСХ введено параметр селективності, що визначається основними конструктивними характеристиками використовуваних дзеркал. Оптимізовано конструкції запропонованих дзеркал з точки зору використовуваних плівкоутворюючих матеріалів. Результати експериментів підтверджують ефективність селекції лазерних переходів з ДЗСХ.