Cavity Mirrors for He-Ne Lasers with Simultaneous Lasing at the Transitions with λ_0 = 0.6328 μm and λ_1 = 3.39 μm

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Abstract

In this work the approach to designing and manufacturing the mirrors for optical cavities of the lasers with simultaneous generation at two different transitions is formulated. Using the model of equivalent layer, the structures of the mirrors for He-Ne lasers operating at the wavelengths of λ_0=0.6328 μm and λ_1=3.39 μm are described. The efficiency of use of the obtained mirrors in serial lasers is demonstrated.

Key words: laser, laser cavity, mirror, thin films

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He-Ne lasers emitting a radiation at λ_1=3.39 μm represent a specific class of quantum electronics apparatus that finds a wide variety of applications. They are used in metrological systems, secondary length and frequency standard systems, gas analysis and environmental monitoring. The important application field for the He-Ne lasers, emitting the radiation at the IR $3s_2$-$3p_4$ transition of neon, is provided by coincidence of the wavelength λ_1 = 3.39 μm with the intensive band absorption of the gaseous methane. The gas leakage indicators based on these lasers have been constructed and successfully operated [1]. A high level of unsaturated amplification for the neon transition with λ_1=3.39 μm stipulates the simplicity of obtaining a lasing action there. With the discharge gap lengths between the active elements larger than 1 m, the transition becomes super-radiant. The power levels for the commercial lasers of this type are rare to exceed 10 mW. This is due to a progressive reach of saturation at such the transition.

When operating the systems, that incorporate this type of lasers, and performing their technological tuning, a problem arises of how to visualise the invisible beam. This can be solved through fitting the systems with an additional small-sized He-Ne laser with λ_0 = 0.6328 μm, or a semiconductor laser emitting the radiation in the visible region of spectrum, the beam of which reproduces suitably the invisible beam path. Such a visualisation method proves to be efficient. However, it results in the systems that appear to be much more complicated on the whole, with their reliability reduced. Moreover, it is not always possible to ensure the precise coincidence of the polar pattern axes for the operating and the technological beams.

For the commercial design of He-Ne lasers, emitting the radiation at λ_1 = 3.39 μm, this shortcoming may be eliminated through introducing a switching from λ_1 to λ_0 [2], though the switching in such the apparatus requires a replacement of the cavity elements.

The interference dielectric mirrors used to achieve simultaneous lasing at the two transitions are multi-component ones. Normally they include coatings with double-unit and, generally, thin-film structures. The optical depth of the individual layers of each unit reaches a value of up to $\lambda_1/4$ [3]. Reducing the total number of layers in the coatings of the double-wavelength laser mirrors is often ensured by the use of metal film [2,3]. Such the optical cavity mirrors feature a rather high Q-factor at the two operating transitions, but they are not efficient in technological terms, since the presence of thick layers substantially decreases a performance of the mirrors, and so that of the laser on the whole.

The latter encourages devising some new designs for the lasers' optical cavity mirrors, which should be both able to operate simultaneously at several wavelengths and free of the disadvantages mentioned above. This task is most commonly solved by a synthesis of thin-film optical coatings, which exhibit the optimal spectrum parameters for the entirety of transitions to be selected. Using the known synthesis methods such as machine-based, graphical and analytical ones and imposing certain restricting conditions make it possible to obtain various structures that meet the specified requirements. However, there is no guarantee for such the solutions to remain within the practicability scope.

The design of thin-film structures for the mirrors is based on the method of equivalent layer. This method has been traditionally used to obtain transparent (anti-reflection) interference coatings for the IR region of spectrum [4]. Developing such the approach to the problem of approximating the reflecting interference coatings has enabled us to construct the cavity mirrors for lasing simultaneously at the transitions considerably distant in wavelength. The example is the transitions with $\lambda_0 = 0.6328$ μm and $\lambda_1 = 3.39$ μm.

Let us consider the elementary symmetric structures that consist of thin layers as follows:

$$B, 3H, B, \lambda_0; \qquad (1)$$

$$H, 3B, H, \lambda_0, \qquad (2)$$

where B and H are respectively the quarter-wavelength dielectric thin films having a high (n_B) and a low (n_H) refractive indices and an optical depth of $\lambda_0/4$ ($\lambda_0 = 0.633$ μm). Within the region of the IR laser wavelength, the elementary structures displayed by (1) and (2) are described with equivalent layer parameters - the equivalent refractive index N_{eq} and the effective phase depth Φ_{ef}.

According to the definitions arising from the matrix method for the analysis of propagation of electromagnetic radiation in symmetric layered media, the mentioned parameters are to be expressed as:

$$N_{екв} = \sqrt{\frac{M_{21}}{M_{12}}}, \qquad (3)$$

$$\Phi_{еф} = \arccos M_{11}, \qquad (4)$$

where M_{ij} are the components of the interference matrix of system of the films.

After analyzing the final pattern of the interference matrix components for the elementary structures (1) and (2), we have determined the following equivalent indices for the structures (1) and (2), respectively:

$$N_{екв} = \sqrt{\frac{n_B \sin 2\Phi \cos 3\Phi + n_H^{-1}\left(n_H^2 \cos^2\Phi - n_B^2 \sin^2\Phi\right)\sin 3\Phi}{n_B^{-1} \sin 2\Phi \cos 3\Phi + n_H\left(n_H^{-2} \cos^2\Phi - n_B^{-2} \sin^2\Phi\right)\sin 3\Phi}}, \qquad (5)$$

$$N_{екв} = \sqrt{\frac{n_H \sin 2\Phi \cos 3\Phi + n_B^{-1}\left(n_B^2 \cos^2\Phi - n_H^2 \sin^2\Phi\right)\sin 3\Phi}{n_H^{-1} \sin 2\Phi \cos 3\Phi + n_B\left(n_B^{-2} \cos^2\Phi - n_H^{-2} \sin^2\Phi\right)\sin 3\Phi}}, \qquad (6)$$

The effective phase depth for the both structures is

$$\Phi_{еф} = \arccos(\cos 3\Phi \cos 2\Phi - \frac{1}{2}\sin 3\Phi \sin 2\Phi\left(\frac{n_H}{n_B} + \frac{n_B}{n_H}\right), \qquad (7)$$

where $\Phi = \frac{\pi}{2\lambda_1}\frac{n_{\lambda 1}}{n_{\lambda 0}}\lambda_0$ and n_λ denotes the refractive index of the layer at the wavelength λ.

Formula (7) testifies that the effective phase depths for the structures (1) and (2) in the λ_1 = 3.39 μm region of λ_1 = 3.39 μm are equal, provided that the spectral dependences of the refractive indices of the layers with the high and low refractive indices are the same $\left(\frac{n_{B\lambda 1}}{n_{B\lambda 0}} \cong \frac{n_{H\lambda 1}}{n_{H\lambda 0}}\right)$. This can be achieved with a high degree of accuracy for the most of film-forming materials,.

Of a practical interest are the elementary structures (1) and (2) which are described by the quarter-wavelength equivalent layer at the wavelength of the IR laser transition with λ_1. Basing on formula (7), one can see that the latter condition is met if

$$tg3\Phi tg2\Phi = \frac{2n_B n_H}{n_B^2 + n_H^2} \quad (8)$$

In other words, it is necessary to find the pairs of materials, for which the refractive index ratios gives the value Φ_{ef} at the wavelength λ_1 equal to π/2. Fig. 1 illustrates the graphical solution of the equation (8).

It is seen from Figure 1 that the coating structures (1) and (2) would be described by the parameters of the quarter-wave equivalent layer in the IR laser transition region, whenever the ratio of the refractive indices for the components is about 1.89. Technologically compatible pairs of the film-forming materials such as zinc selenide ($ZnSe$, n_B = 2.5) and cryolite (Na_3AlF_6, n_H = 1.33-1.35) better meet this condition.. The parameters of equivalent refractive indices of this pair for the structures (1) and (2) are calculated as 1.52 and 2.20, respectively. Thus, the structure (1) in theregion of λ = 3.39 μm can be presented as a quarter-wave layer with a low refractive index, while the structure (2) as a quarter-wave layer with a high refractive index. Basing on these results and using the general principles of building up the interference reflecting coatings, the thin-film structures with a high reflection at λ_1 and λ_0 can be presented as either:

$$S_0 \ (H,3B,H),(B,3H,B),...,(H,3B,H), \quad \lambda_0=0.633 \text{ mm}, \quad \text{B-ZnSe, H-}Na_3AlF_6 \quad (9)$$

or

$$S_0 \ [((H,3B,H),(B,3H,B)]_{(K-1)/2}(H,3B,H), \quad \lambda_0=0.633 \text{ mm}, \quad \text{B-ZnSe, H-}Na_3AlF_6 \quad (10)$$

where S_0 –stands for the substrate from a material being simultaneously transparent at the transitions with λ_0 and λ_1, and K = 1,3,5...

Table 1 contains the quantities calculated for the thus synthesized structures of mirrors (9) at the wavelengths of operating transitions and for the various values of the parameter K.

Let us now take into account that the most of He-Ne lasers have the discharge gap of up to 2 m and the inner diameter of the capillary

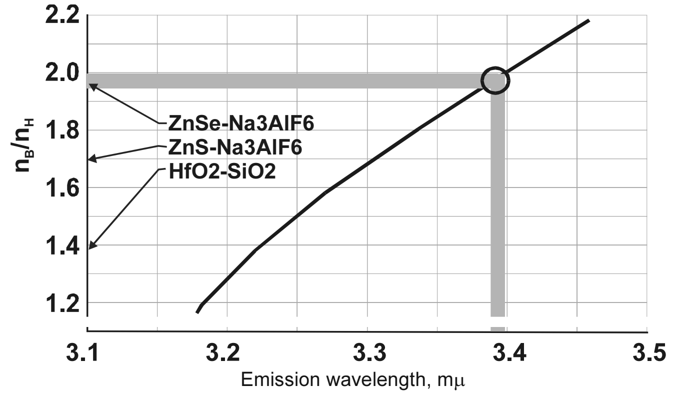

Fig. 1. The emission wavelength, as calculated from (8), versus the n_B/n_H ratio for the elementary structures (1) and (2) corresponding to $\Phi_{ef} = \pi/2$.

Table 1. The calculated values of reflection at the wavelengths λ_0 and λ_1 for different numbers of layers in the structure (10), when using the substrate from the material based on optical quartz glass (n_S = 1.45)

No	Pairs of the materials used	Values of the parameter *K*	Reflection coefficients, % at	
			λ_0	λ_1
1	ZnSe - Na_3AlF_6	2	96.8	55.1
2	ZnSe - Na_3AlF_6	3	99.1	74.0
3	ZnSe - Na_3AlF_6	4	99.9	87.5
4	ZnSe - Na_3AlF_6	5	99.9	93.5

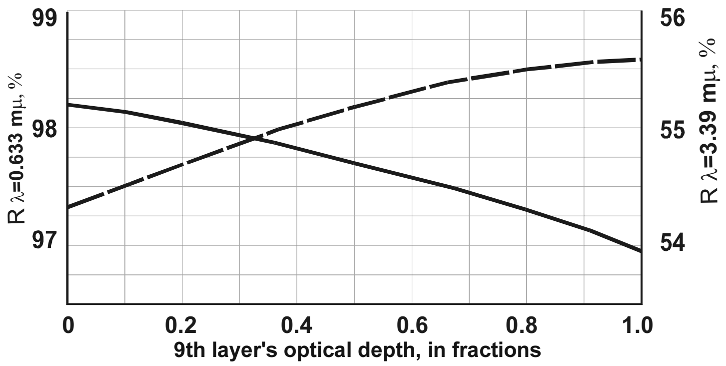

Fig. 2 The reflectance of the mirror with the thin-film structure represented in Table 1 in the region of the operating transitions versus the optical depth of the 9th layer: *1 - for λ_0 = 0.633 μm; 2 - for λ_1 = 3.39 μm*

tube's about 1.5 – 5.0 mm. Then the optimal values of the reflection coefficients are within the following limits: *R(0.633)* ≃98.5 – 96.5% and *R(3.39)* ≃40 – 60% for the “output” mirror; and *R(0.633)* > 99.8% and *R(3.39)* > 90.0% for the “100 %” mirror. The structures 1 and 4 in Table 1 can be therefore recognized as the optimal ones, since they best meet the requirements specified above.

More precise values of the reflection for the more critical $3s_2$-$2p_4$ transition (λ_0 = 0.6328 μm) and the structure 1 (Table 1) can be obtained by varying the thickness of the last ninth layer. Fig. 2 shows the reflectance at the laser operating transitions versus the optical depth of the ninth layer (Na_3AlF_6, in fractions of $\lambda_0/4$). One can easily see that a variation of the optical depth of this layer allows for obtaining the reflectivity changes in the transition region with λ_0= 0.6328 μm, which extend over the full range of values necessary for the "output" mirror. In addition, the changes in the reflection at λ_1= 3.39 μm do not go beyond the range necessary for that transition.

The vacuum deposition technique for synthesizing the structures of the optical cavity mirrors is similar to that typical for the class of coatings from dielectric film-forming materials. The manufacturing process is based on the vacuum resistance spraying of the materials such as ZnSe and cryolite, using the plants of URM type [5]. The reflectance spectra of the laser mirror obtained this way are illustrated in Fig. 3. The results of testing these mirrors in demountable cavities with various types of active elements are given in Table 2.

The data presented in Table 2 have been averaged, basing on the results of studies carried out on at least five active elements of each type and five sets of the manufactured mirrors. The power measurements have been performed using the IMO-2M-type power-meter. For, there have been used The plates made from the optical colourless glass LK-4 (to select λ_0= 0.6328 μm) and germanium (to select λ_1=3.39 μm) and polished to a high degree of surface quality have been used as the external selecting elements. The account of the Fresnel losses at the plate surfaces has been also taken in the final estimations of the output power.

Table 2. The results of testing the optical cavity mirrors in demountable resonators

No	Type of active element	Power values obtained in dual-line lasing, mW	
		λ_0=0.6328 μm transition	λ_1=3.39 μm transition
1	GL-44	2	0,8
2	GL-113	8	3.0
3	GL-120	12	4.5
4	GL-222	22	10.5

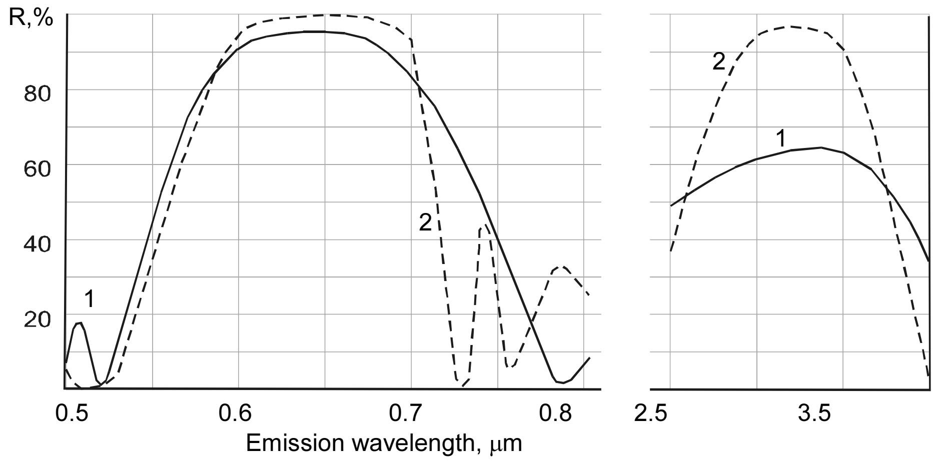

Fig. 3 The reflectance spectra of the mirrors with thin-film structures corresponding to: *1 - 1, table 1; 2 - 4, table 1*

The power levels obtained on different types of the readily available active elements remain within the allowable range of values required by the systems referred to above. The simplicity of the thin-film structures synthesized by us for the optical cavity mirrors of dual-line He-Ne lasers and, moreover, the use of typical technologies for this purpose prove that the approaches chosen in this work for designing them are right. This, in turn, makes it possible to start with developing a new class of atomic gas lasers, and the systems on their basis.

References

1. Bublithenko I.A., Mohnonozjkin B.E. The laser gas analyzer for search of outflow of gas from underground gas pipelines // Pribory i Tekhnika Eksperimenta., - 1999.- No5.- p.126-129. (in Russian).
2. Bondarchouk J.M. Optical elements of lasers of a visible area // Fizychnyi Zbirnyk NTSh – 1996- V.2. - p.138-147. (in Ukrainian)
3. Popov A.I, Protcenko E.D. Skachkov U.F. Dielectrics for covering mirrors for the two-wavelength lasers generating at 0.63 μm and 3.39 μm // Zh. Prikl. Spektr. 1977. - 27, №1.- p.37-41.(in Russian).
4. Bondarchouk J.M., Voznjak R.M., Korbetcki R.V. Privalov V.E. Helium-neon lasers at weak transitions in neon. // Reviews on Electronic Engineering, 2, Laser Engineering and Optoelectronics, 1990.- v.8.- 56 p.
5. Bondarchuk J.M., Technology and processing of optical materials: the scientific edition. - Lviv: League - Press, 2001. - 242 p. (In Ukrainian).