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CONTROL OF LASER RADIATION PARAMETERS

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Switching of lasing wavelength in a sol – gel laser with dynamic distributed feedback

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***Abstract*. A scheme of switching the lasing wavelength of active centres in a sol – gel matrix excited by external laser radiation is proposed. A distributed feedback is formed during pumping by using a right-angle prism due to the interference of the direct and reflected pump beams. The lasing wavelength is determined by the period of the interference pattern, which depends on the convergence angle of interfering beams. Control is performed by a liquid-crystal cell, which changes the pump radiation polarisation, and a birefringent prism. As a result, the convergence angle of interfering beams changes, leading to a change in the interference pattern period and the excited radiation wavelength.**

Keywords: *dye laser, sol – gel matrix, dynamic distributed feedback, liquid-crystal cell.*

1. Introduction

Miniature solid-state lasers on active centres are widely used in laser technique, especially in information technologies. These lasers can be excited by either an electric current or radiation of another laser. Feedback in these structures is formed by changing periodically the optical parameters of the active medium [the so-called distributed feedback (DFB)] [1]. In this case, the generated radiation propagates along the layer doped with active centres (active layer), i.e., waveguide lasing is implemented.

The regular modulation of active-layer optical parameters can be constant, in the form of a stationary periodic change in the refractive index across the sample. This DFB is referred to as morphological. In addition, in the case of pumping by another laser, the optical parameters (for example, the active-medium gain) can be modulated only during pumping. The DFB of this type is referred to as dynamic or light-induced; it can be implemented upon excitation of the active layer through a periodic mask (holographic grating) or as a result of interference of coherent pump beams. The distributed feedback induced by pump-beam interference is also referred to as holographic DFB.

Thin layers of liquid dye solutions [2, 3]; dye-doped polymers [4 – 6]; dye-containing liquid-crystal (LC) layers [7 – 9]; and glass matrices with active centres, obtained by the sol – gel process [10, 11], can be used as active media for waveguide lasers.

Currently, much attention is paid to solid-state lasers on active centres, which are promising for photonic (including display and laser) technologies and telecommunications. Solid-state lasers on active centres with a dynamical DFB generate short pulses with narrow emission lines and, therefore, are promising as compact coherent light sources. Thin-film waveguide lasers are necessary for effective incorporation into planar waveguide circuits. In the majority of practical applications in integrated optics rectangular dielectric waveguides are most often used; many active or passive devices (waveguide filters, optical switches, multiplexers, etc.) are based on them.

Glass waveguides have certain advantages over polymer ones due to the higher refractive index, which makes it possible to form waveguide films on many substrates (borosilicate glasses, quartz, fused silica, polymers, etc.). In addition, the transparency in the short-wavelength range of the spectrum allows one to obtain lasing in the UV and blue-green regions. Inorganic glasses doped with active centres can be prepared by the low-temperature sol – gel technology. The sol – gel method is suitable for preparing active elements, because active centres of various types (rare earth elements, semiconductors, organic dyes, etc.) can be incorporated into a glass matrix.

The lasing wavelength λ_g under holographic pumping is determined by the Bragg condition and depends on the refractive index n of the active medium and the convergence angle 2θ of interfering beams:

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$$\lambda_g = \frac{n\lambda_p}{M\sin\theta}, \tag{1}$$

where λ_p is the pump wavelength and M is the Bragg diffraction order. Accordingly, the lasing wavelength under holographic pumping can be controlled by changing either the effective refractive index of the active medium or the convergence angle of the excitation beams.

Controlling the lasing wavelength in a waveguide laser under holographic pumping by changing mechanically the angle of incidence of the pump beam was demonstrated in [10, 11]. In addition, the lasing wavelength can be changed by applying an electric field, which affects, for example, the LC (active medium) orientation [7, 8]. Note that the control of the lasing wavelength by an electric field is much superior to mechanical control in speed, reliability, and technical simplicity. However, solid-state lasers are more convenient for applications than lasers with liquid active media. In this study, we proposed and implemented a method for switching the lasing wavelength in a solid-state laser based on a dye-containing sol – gel matrix using an electric field to change the angle of incidence of the pump beam.

2. Experimental

Figure 1 shows a schematic diagram of the laser element, which clarifies the way for obtaining lasing with a switched wavelength by changing the angle of incidence of the pump beam. Excitation is performed by the second harmonic of an Nd^{3+} : YAG laser, using a right-angle prism. The pump beam passes through a polariser (*1*) and is expanded by a telescopic system, composed of two lenses, (*2*) negative and (*3*) positive. Then it is focused by a cylindrical lens (*4*) into a narrow thin strip and passes through an electro-optical deflector (*5*). Furthermore the beam is incident on the hypotenuse face of the right-angle prism (*6*) with a reflecting layer (*7*) deposited on one of its side faces. A sample of a sol – gel glass plate (*9*), doped with active centres (dye rhodamine 4C), is fixed on the other side face of the prism. The optical contact of this sample with face (*8*) of the prism is provided by an immersion layer (silicon oil). Some part of pump radiation is incident directly on the face contacting with the sol – gel sample. The rest of pump radiation arrives at the perpendicular face of the prism with a deposited chromium layer, reflects off from it, and finally arrives at the face contacting with the sample to form an interference pattern. This pattern is a set of alternating dark and bright fringes with a period d, which is determined by the formula

$$d = \frac{\lambda_p}{2n_1\sin\{\beta - \arcsin[(\sin\varphi)/n_1]\}}. \tag{2}$$

Here, n_1 is the refractive index of the prism material; β is the angle of the prism that is adjacent to the side face on which interference occurs; and φ is the angle of incidence of the pump beam on the hypotenuse face. Lasing arises, the wavelength of which is determined by the Bragg condition (1):

$$\lambda_g = \frac{n\lambda_p}{n_1 M\sin\{\beta - \arcsin[(\sin\varphi)/n_1]\}}. \tag{3}$$

It follows from (3) that a change in the angle of incidence of the pump beam on the prism face, φ, should lead to a change in the pump modulation period and, correspondingly, a change in the lasing wavelength.

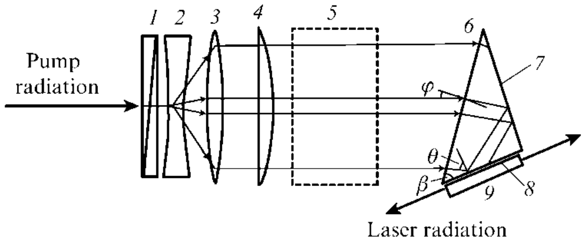

Figure 1. Schematic diagram of the laser element: (*1*) polariser, which provides a necessary linear polarisation of light; (*2*) negative lens; (*3*) positive lens; (*4*) cylindrical lens; (*5*) electro-optical deflector; (*6*) right-angle prism; (*7*) reflecting layer of the right-angle prism; (*8*) silicon oil layer, which ensures an optical contact between the sol – gel sample and prism; and (*9*) sol – gel sample doped with active centres.

The lasing wavelength is switched using a field-controlled electro-optical deflector (Fig. 1), which consists of an LC twist cell and a birefringent prism (see schematic in Fig. 2). The LC cell contains glass substrates (*1*) (glass K8). Transparent electrodes (*3*) (indium oxide and tin oxide layers) are deposited on the inner surfaces of the glasses. The glass substrates are separated by Teflon spacers (*2*), which specify the LC layer thickness d. A nematic liquid crystal (NLC) (*6*) (ZhKM-1289, NIOPIK) is placed between the glasses. The refractive indices of ZhKM-1289, $n_{\parallel}$ and $n_{\perp}$ for the directions parallel and perpendicular to the LC director, are 1.678 and 1.510, respectively. The transparent electrodes are coated by an orienting polyimide layer to form a planar (i.e., lying in the layer plane) LC orientation on the surface of glasses. The orientation direction is set by rubbing surfaces in mutually perpendicular directions on each glass. This LC cell is referred to as a twist one. Connecting wires (*4*) are soldered to the transparent electrodes to apply voltage to the cell.

The principle of deflector operation is as follows. A linearly polarised pump beam with a wavelength λ_p, having passed through the cylindrical lens, is incident on the LC twist cell. If the NLC parameters and the cell thickness

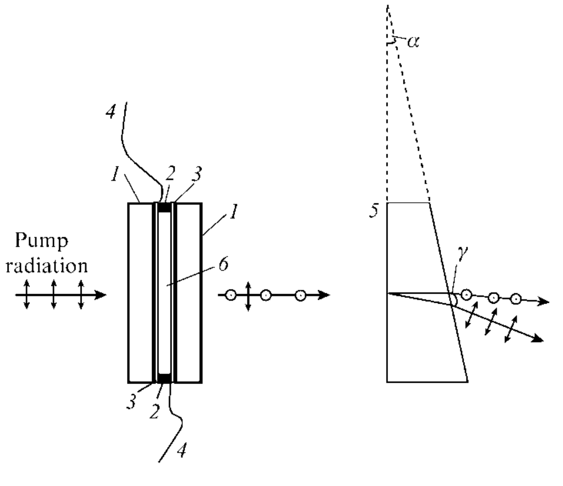

Figure 2. Schematic of the electro-optical deflector: (*1*) glass; (*2*) spacers, which specify the thickness of the LC layer; (*3*) transparent conducting coatings; (*4*) connecting wires for applying voltage to the cell; (*5*) birefringent prism; and (*6*) NLC layer.

satisfy the Mauguin condition $\lambda_p \ll (n_{\|} - n_{\perp})d$, the twist cell changes the polarisation direction of the linearly polarised light transmitted through it by 90°. Application of voltage to the NLC twist cell changes its orientation from planar-twisted to homeotropic. In this case, the light transmitted through the twist cell retains the initial polarisation direction. Thus, one can use a twist cell to switch the linear polarisation direction of light by 90°.

The linearly polarised light transmitted through the twist cell passes then through the right-angle birefringent prism (*5*) with a vertex angle α (Fig. 2). Generally, two beams propagate in a prism: ordinary and extraordinary; the refraction angles for these beams are determined by the corresponding refractive indices, n_o and n_e, respectively. One can choose the linear polarisation direction and the directions of the principal axes of the birefringent material so that make only one beam (ordinary or extraordinary) propagate in the prism. Figure 2 shows the birefringent prism (*5*), whose optical axis is parallel to its large side face and perpendicular to the small side face. If linearly polarised light with a polarisation direction parallel to the optical axis of the prism is normally incident on its large side face, only extraordinary beam will propagate in the prism. If the polarisation direction of the incident beam is perpendicular to the optical axis, there will be only the ordinary beam in the prism. The angle γ between the ordinary and extraordinary beams at the output of the prism is determined by the relation

$$\gamma \approx \alpha(n_e - n_o). \tag{4}$$

Thus, switching the voltage across the twist cell changes the pump radiation polarisation at its output, and the angle of incidence of the pump beam on the laser element changes at the output of the birefringent prism to change the lasing wavelength.

3. Experimental results

The pump radiation, which is the second harmonic of an Nd^{3+} : YAG laser, polarised in the plane of Fig. 2 (the polarisation direction is indicated by arrows), is incident on the LC cell. At zero voltage across the cell the light changes its polarisation to orthogonal, and its polarisation direction is perpendicular to the plane of Fig. 2 at the output of the cell (the polarisation direction is indicated by circles with points). With a voltage applied across the cell, the light at its output retains the initial polarisation in the plane of Fig. 2. Then the light is incident on the birefringent prism (made of calcite Ca_2CO_3) with the refractive indices $n_e = 1.660$ and $n_o = 1.487$ (the prism vertex angle $\alpha = 15°$) and deviates by some angle, which depends on the polarisation direction of light. The angle γ between the rays with orthogonal polarisation directions, according to formula (4), is $\sim 2°35'42''$. Then the pump beam with a particular polarisation is incident on the hypotenuse face of the right-angle prism (*6*) (glass K8) with a vertex angle $\beta = 60°$ (Fig. 1). This geometry of the laser element provides lasing near 600 nm for the Bragg diffraction in the first order. A chromium coating with a reflectance of 70 % is deposited on the side face of the prism *6* that makes an angle of 30° with the hypotenuse face. The active element (sol–gel glass) $10 \times 10 \times 2$ mm in size, doped with laser dye rhodamine 4C to a concentration of 6×10^{-5} M, is attached to the other side face with the aid of an immersion liquid. When the pump beam is incident on the hypotenuse face at the angle $\varphi = 0$, the lasing wavelength λ_g, in correspondence with formula (3), is 592.0 nm. Application of voltage to the LC cell changes the angle of incidence of the pump beam by $2°35'42''$, and the lasing wavelength becomes 602.7 nm. The lasing spectra for the laser element of this geometry are shown in Fig. 3.

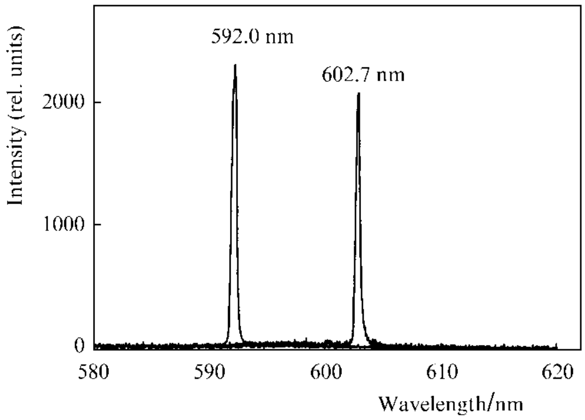

Figure 3. Lasing spectra of the laser element based on a birefringent prism with the vertex angle $\alpha = 15°$. The lasing wavelength λ_g is 592.0 nm at zero voltage across the LC cell and 602.7 nm with a voltage switched on.

If the vertex angle of the birefringent calcite prism is $\sim 4°$, the angle γ between the beams with orthogonal polarisations, in correspondence with formula (4), is $\sim 41'31''$, and the angle of incidence of the pump beam, φ, is 4° at zero voltage across the LC cell. In this case, the lasing wavelength $\lambda_g = 608.8$ nm [in correspondence with formula (3)]. With a voltage across the LC cell, the angle of incidence of the pump beam changes by $41'31''$, and the lasing wavelength is ~ 612.0 nm. The lasing spectra for the laser element of this design are presented in Fig. 4.

Thus, the tunable lasing wavelength can be varied in a wide spectral range, which depends on the dye type and the initial angle of incidence φ of the pump beam. The difference in the switched wavelengths depends on the geometry and refractive indices of the birefringent prism. The switch-

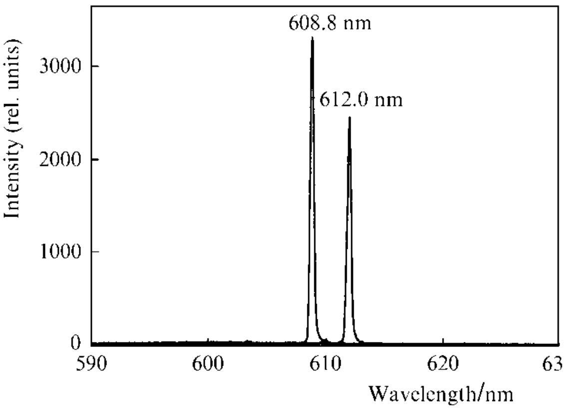

Figure 4. Lasing spectra of the laser element based on a birefringent prism with the vertex angle $\alpha = 4°$. The lasing wavelength λ_g is 608.8 nm at zero voltage across the LC cell and 612.0 nm with a voltage switched on.

ing time of this device is determined by the response time of the LC twist cell.

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