Chapter 20

Active Holography

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Additional information is available at the end of the chapter

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Abstract

The laser active structures with spatial modulation of lasing controlled by the transversely distributed excitation are implemented. The dye-doped cholesteric liquid crystal (DD CLC) and polymer were used as a laser active medium. The interference pattern of two coherent pumping beams was used for excitation of the laser layers. The second harmonic of a Q-switched Nd:YAG laser (532 nm) was used for the pumping. The interference pattern of the pumping light was located in the plane of the laser active layer. The emission of lasers was observed perpendicular to laser active layers from the opposite side of the incidence of the pumping light. The periodical character of the modulation of intensity along cross section of the lasing depends and corresponds to the parameters of the interference pattern of the pumping. So, the emitted light field qualitatively looks like a diffraction from an elementary hologram, and obtained lasers can be called as active elementary hologram.

Keywords: coherence, pumping, DD CLC laser, dye laser, diffraction, holography

1. Introduction

The method of holography has undergone enormous development since the discovery [1] (1948) up to the present time. The holography also has made great strides in the development of many scientific methods and many technological problems starting with the simplest holograms and ending by the digital holograms [2–4]. Especially it should be noted that already is reached the holographic recording and reconstruction of almost all parameters of the light wave—amplitude, phase, wavelength, and polarization characteristics [5–19]. Anyway the main stage of the holographic process is the creation of the diffractive structure corresponding to distribution of relative phase of the object and reference waves. On this basis, it was possible to say that holography has almost exhausted its potential for further development, but it turned out that there are certain prospects in terms of new nonstandard approaches.

As it is known, conventional holograms including dynamic represent passive diffractive elements. This means that the reconstruction of the recorded holographic information requires existence of the external source of the light. The light from the external light source is incident on the holographic diffraction structure and diffracting and reconstructs the initial wave front of the light scattered by the object.

However, it is possible to create a structure in which its individual microareas corresponding to the holographic structure can themselves emit mutually coherent radiation. In this case, the reconstruction of the wave front which carries information about the object is possible by laser radiation of this structure but not due to diffraction of light incident from outside. According to the author's opinion, this approach, in addition to the initiation of interesting new research in the field of laser physics and holography, can support to develop optical information technologies and in particular in the technology of holographic 3D displays.

At present, all old and modern methods of obtaining stereoscopic effects are considered for the 3D display tasks. In particular, they are using the earliest approaches of the raster stereoscopic and polarization methods, which require using additional auxiliary equipment in the form of passive glasses or active polarized glasses. From the modern achievements, so-called voxel displays should be noted, when the image is formed by voxel-glowing dots within a certain volume the display. In all of these cases, 3D image represents pseudoimages of the perception which is subjective that is perceived by specific characteristics of human visual system, in particular, by the binocular vision and visual inertia. Holographic images do not require additional raster systems and specific glasses for perception. However, as it was mentioned above, the known holographic structures (holograms) are passive diffraction structures.

In difference of this, the holographic structures (holograms) that reconstruct the wave front of light scattered by the object by own laser radiation might be termed as active holograms.

Laser active holographic structures are fundamentally different because the reconstruction of optical information, in this case, takes place not as a result of diffraction of incident outside light wave, but it is carried out by laser radiation, generated by these structures. Usual holograms represent oneself certain distribution of microscopic optical heterogeneity and implement passive transformation (diffraction) of the light wave (**Figure 1**). The diffraction of the outside light wave on such a structure reconstructs wave front of the light scattered by an object.

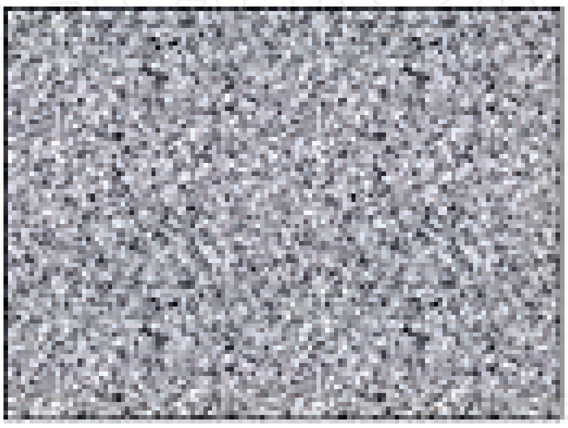

Figure 1. General structure of the usual hologram.

Now let us assume that all of the microscopic heterogeneity of such a holographic structure represent oneself mutually coherent microlasers. In this case the summary lasing of such a structure will create the wave front analogous to the previous, i.e., will reconstruct of the image of the object but on the wavelength of own radiation. Thus, such a device might be termed as an active holographic structure, and such a method might be termed as an active holography.

The first results in this direction have been obtained in the layer of cholesteric liquid crystal (CLC) doped by the dye 4-Dicyanomethylene-2-methyl-6-p-dimethylaminostyryl-4H-pyran (DCM) and in the layer of polyvinyl alcohol (PVA) doped by dye Rhodamine 6G [20–28].

2. Holographic laser on the basis of dye-doped cholesteric liquid crystal (DD CLC)

A new type of CLC laser with the transversely distributed excitation was realized first time in the DD CLC. The interference pattern of two coherent pumping beams of the second harmonic of a Q-switched Nd:YAG laser (532 nm) was used for the pumping. The interference pattern was located in the plane of the laser active layer [21, 25]. The laser radiation of the DD CLC layer was observed perpendicular to the laser cell from the opposite side of the incidence of the pumping light. Emitted laser field is modulated spatially. The periodical character of the modulation of intensity along cross section of the lasing depends and corresponds to the parameters of the interference pattern of the pumping, and the pattern of the emitted light field qualitatively looks like a diffraction from an elementary hologram.

Periodical spatial modulation of such a picture of lasing is connected with characteristics of coherence of obtained DD CLC laser. Particularly, the interference pattern of the pumping beams creates periodical distribution of intensity in the plane of the DD CLC laser layer for its excitation, forming a laser structure representing a periodical set of microlasers. The total interference pattern of emission from these microlasers forms the lasing picture which looks like a diffraction from a periodical structure. So, obtained laser can be considered as a laser and, at the same time, as an elementary hologram simultaneously.

Figure 1 shows the scheme of the experimental setup of the double-beam pumping of the laser cell. The second harmonic (λ_p = 532 nm) of the Q-switched **Nd^{3+}:YAG** laser is divided into two mutually coherent beams of equal intensity with the help of beam splitter. The beam splitter was composed of two laser mirrors with reflectance of 50% (1) and 99.9% (2) for the wavelength of 532 nm. The distance of 15 mm between the mirrors (1) and (2) of the beam splitter provided a stable interference pattern. The duration of the pulses was 15–20 ns. The excited, by the pumping laser, spot on the DD CLC layer has a size 1–2 mm.

Such an experimental setup (**Figure 2**) ordinarily is used for the recording of the holographic gratings and for the pumping of the dye distributed feedback (DFB) lasers. So, the pumping light field in this case represents oneself the interference pattern as a periodically arranged bright and dark strip (**Figure 3**). The period d of the interference pattern of the pumping light is determined by the well-known formula [4, 29, 30]:

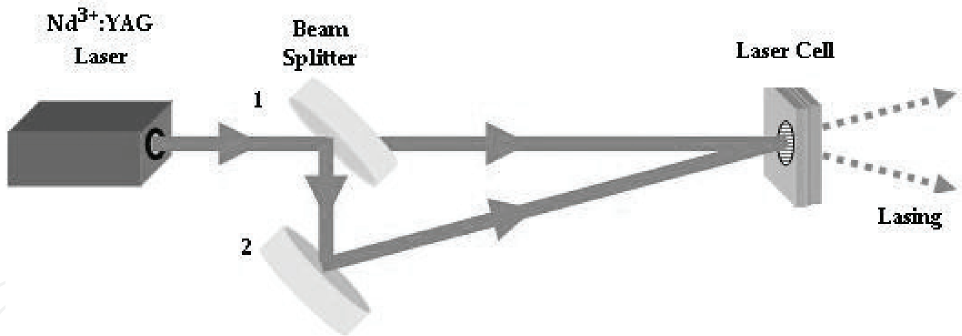

Figure 2. Scheme of double-beam coherent pumping.

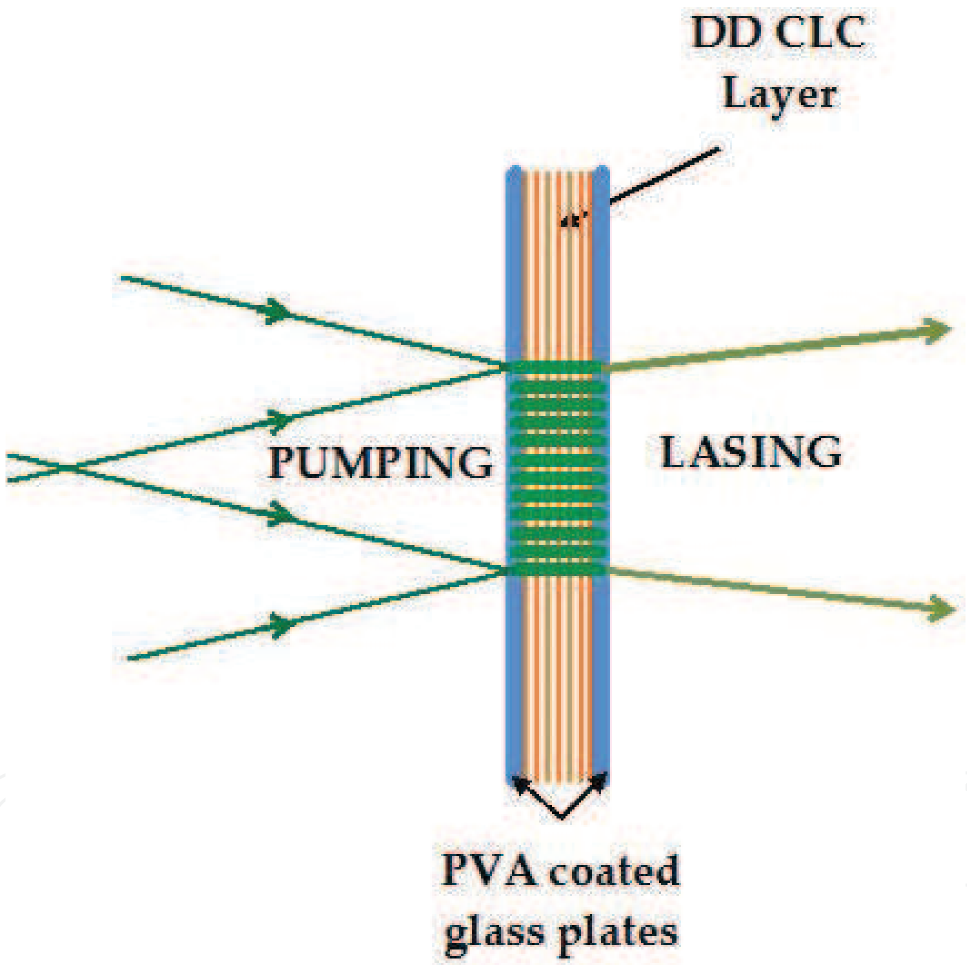

Figure 3. Formation of the interference pattern of the pumping in the DD CLC layer.

$$d = \frac{\lambda_p}{s \sin(\theta/2)} \tag{1}$$

where λ_p is the wavelength of pumping and θ is the convergence angle of the pumping beams.

As a result, an array of microlasers was obtained which emit light simultaneously in perpendicular direction regarding to DD CLC laser layer. The picture of the array of microlasers

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was observed by microscope and was fixed by digital camera (**Figure 4**). **Figure 4(a)** and **(b)** corresponds to the convergence angles of **1.8**° and **0.6**° for the pumping beams accordingly. Thus, microlasers were formed as a separate strips of lasing the width of which depends on the angle between pumping beams.

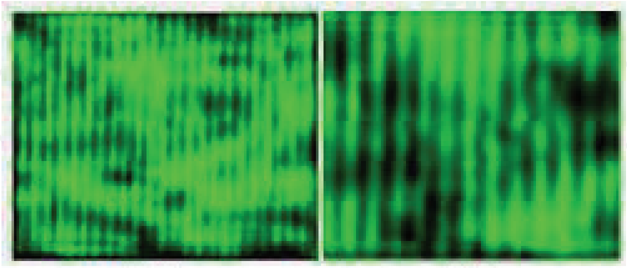

Figure 4. Array of microlasers in the DD CLC layer.

The DD CLC laser cell was prepared by conventional, well-known technology. For the active laser medium, dye DCM exciton was used, which was introduced in the CLC matrix.

A mixture of nematic liquid crystal BL-036 and optically active component MLC-6247 (both from Merck) was used as a CLC matrix where 0.4% of DCM (exciton) was added. The period of the helix of the CLC mixture was about 370 nm. The thickness of the obtained plane parallel layer of the CLC was approximately 40 μ. Glass plates for the windows of the CLC laser cell were precoated with thin layers of polyvinyl alcohol (PVA) and are oriented by rubbing.

The spectrums of transmission and fluorescence of the DD CLC laser cell are shown in **Figures 5** and **6**, respectively. **Figure 7** shows the lasing spectrum. Thus, according to results presented in **Figures 6** and **7** regarding the spectral characteristics of emission, this laser does not differ from the known DD CLC lasers with the single-beam pumping. However, the difference, caused by the excitation with the interference pattern of two mutually coherent beams, is manifested in the structure of the cross section of the emitted beam. In **Figure 8(a)** and **(b)**, the photos of the cross section of lasing for the angles **1.8**° and **0.6**° between the pumping beams are shown. It is seen that the intensity distribution along the cross section of lasing has the periodical character, which differs from distribution of intensity of lasing of conventional CLC lasers and looks like the diffraction from the diffractive grating.

The distance between the maximums (or minimums) of intensity of the pattern of lasing in **Figure 8(a)** and is approximately 2.3 mm (a) and 6.5 mm (b) accordingly, and the distance from the CLC layer to the screen is 20 cm. Thus, according to the calculation, the angles between the directions of propagation of the nearby maximums, from the excited spot of the CLC layer, have values **1.86**° and **0.66°** that closely enough agrees to angles of diffraction **1.81**° and **0.64**° from the diffractive grating calculated by the formula [4, 29, 30]:

$$\varphi = 2 \arcsin\left(\frac{\lambda_p}{2d}\right) \tag{2}$$

where λ_p is the wavelength of lasing of the DD CLC laser cell and ***d*** is the period of the interference pattern of pumping. The modulation of the intensity of the emission pattern of lasing disappears when one of the pumping beams is shutting (**Figure 8(c)**).

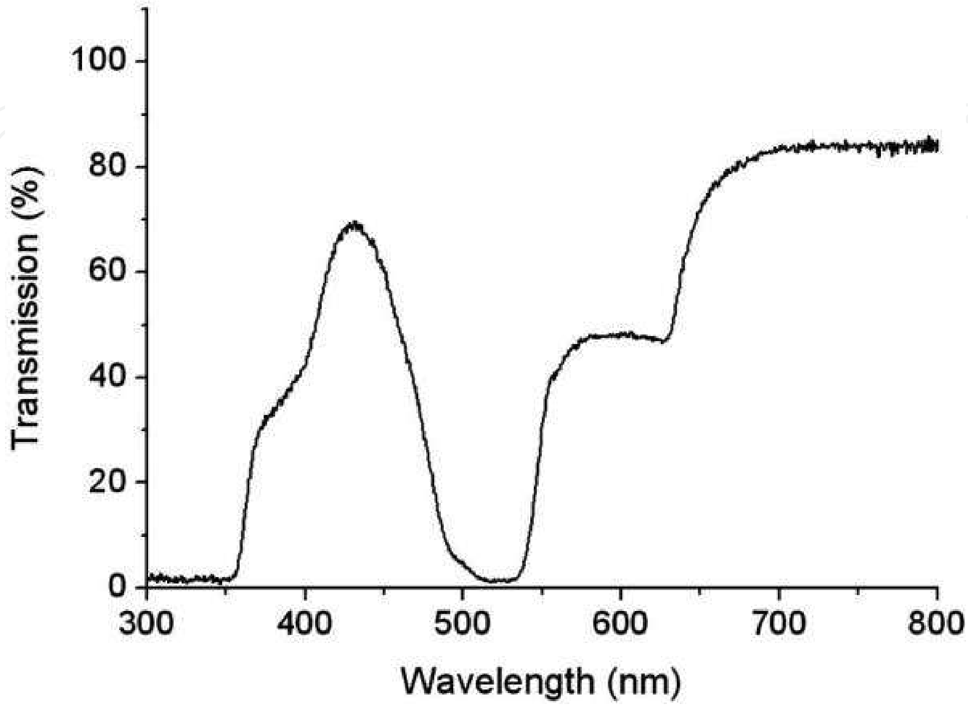

Figure 5. The spectrum of optical transmission of the DD CLC cell along the cholesteric helical axis.

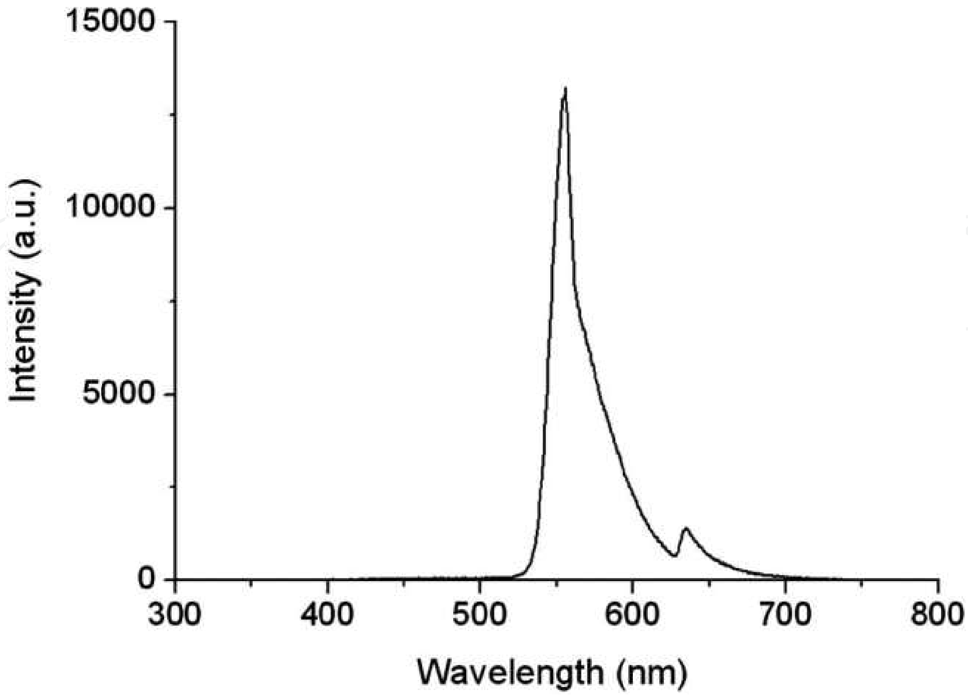

Figure 6. The spectrum of fluorescence of the DD CLC laser cell.

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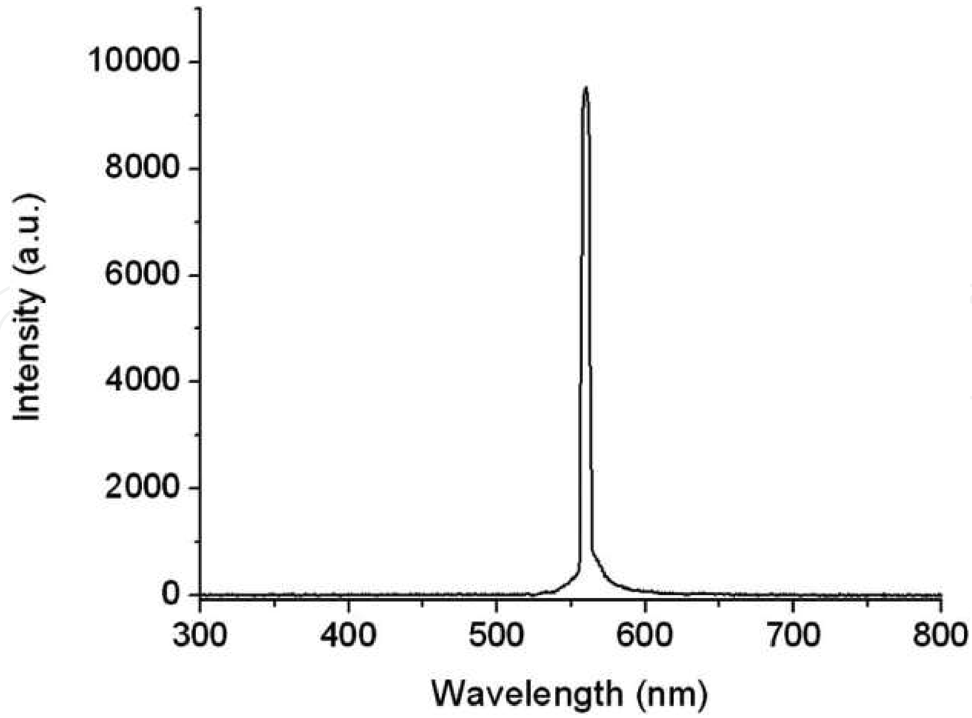
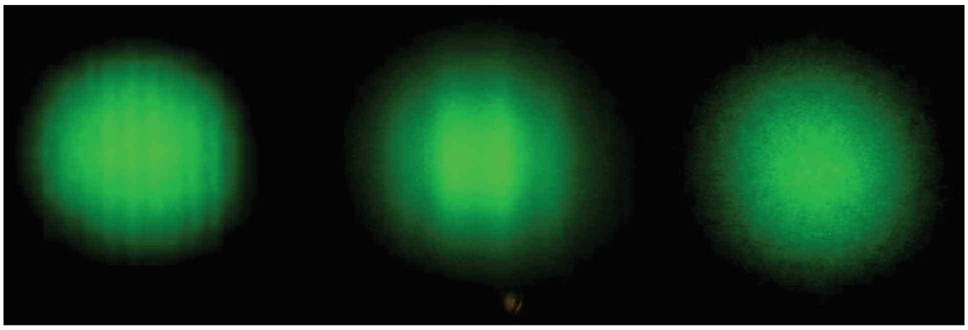


Figure 7. Lasing spectrum of the DD CLC cell.



a b c

Figure 8. Picture of lasing from DD CLC laser cell at the pumping by interference pattern of two beams (a, b) and at the pumping by one beam (c). The convergence angles of the pumping beams are 1.8° (a) and 0.6° (b). The spatial period of the pumping interference patterns is 17 and 50 μ, respectively.

In author's opinion, the spatial modulation of laser emission field is a result of the mutual correlation between the emitting centers of the individual strips of radiation. Probably, correlation effects, in this case, are of the same nature that provides spatial coherence in the conventional lasers. Thus, the emitting area, of the described laser cell, represents a periodical structure of the mutually coherent microlasers. The total radiation of such a periodical structure, according to the Huygens-Fresnel principle, must form summary interference pattern similar to that shown in **Figure 8(a)** and **(b)**. This phenomenon is similar to the formation of the diffraction pattern from the diffractive grating of the corresponding periodical structure from the point of view of Huygens-Fresnel principle.

Probably, the main factor in reducing the contrast of the spatial modulation of the pattern of lasing is the significant value of the scattering of the light that is characteristic of liquid crystals

(**Figure 8(a)** and **(b)**). The new type of a laser, which combines the properties of a laser and a hologram, was firstly realized on the basis of a DD CLC layer. The field of emission of this laser has a spatial modulation with the periodical distribution of the intensity, controlled by the transversely distributed excitation. Therefore, the spatial distribution of the emission intensity in this case carries out information about the interference pattern of the pumping that makes it similar to the elementary hologram, i.e., holographic diffractive grating. Thus, according to results presented in **Figures 6** and **7** regarding to the spectral.

3. Laser active elementary holographic structure on the basis of dye-doped polymer film

Spatial modulation of laser emission controlled by the structure of the excitation light field was obtained also in the dye-doped polymer film [21–28]. The dye-doped polymer film as an active medium was sandwiched between two laser mirrors forming a laser cavity. The pumping was performed by an interference pattern, formed with two mutually coherent beams of the second harmonic of a Q-switched Nd:YAG laser (532 nm), located in the plane of the laser cell. The laser emission was observed normally to the plane of the laser cell.

The cross section of the obtained laser emission was modulated in intensity with an interval between maximums that depends on the period of the interference pattern of the pumping. Thus, the emitted light field qualitatively looks like a diffraction from an elementary dynamic hologram, i.e., a holographic diffraction grating.

An elementary hologram (holographic grating) usually represents a passive diffractive device. In obtaining information about the recorded holographic structure, an external light source is required.

However, as it is known, diffraction is the result of interference of secondary waves from all lines of the optical heterogeneity of the periodical structure of the grating [29, 30]. Therefore, if we have a periodical structure each strip of which is emitting mutually coherent light waves, the total light field will be analogous to a passive diffraction picture. Such a result was already observed during the study of the coherence of emission of the DD CLC laser. In this case, the excitation also was performed in the form of an interference pattern of pumping beams.

The interference of the laser beams is used in various spheres of science and technology and, among them, for achieving laser emission. In particular, double-beam coherent pumping has long been used for obtaining of the distributed feedback (DFB) in dye lasers [31–36]. In these cases the mutually coherent pumping beams in the active medium form an interference pattern whose bright and dark strips are distributed along generated laser emission (**Figure 9**). But the correlation between the emitting centers in the emitting strips of the active medium allows not only formation DFB in the dye lasers. For instance, as it was shown for the DD CLC laser, the excitation by the interference pattern gives rise to the spatial modulation of the laser emission.

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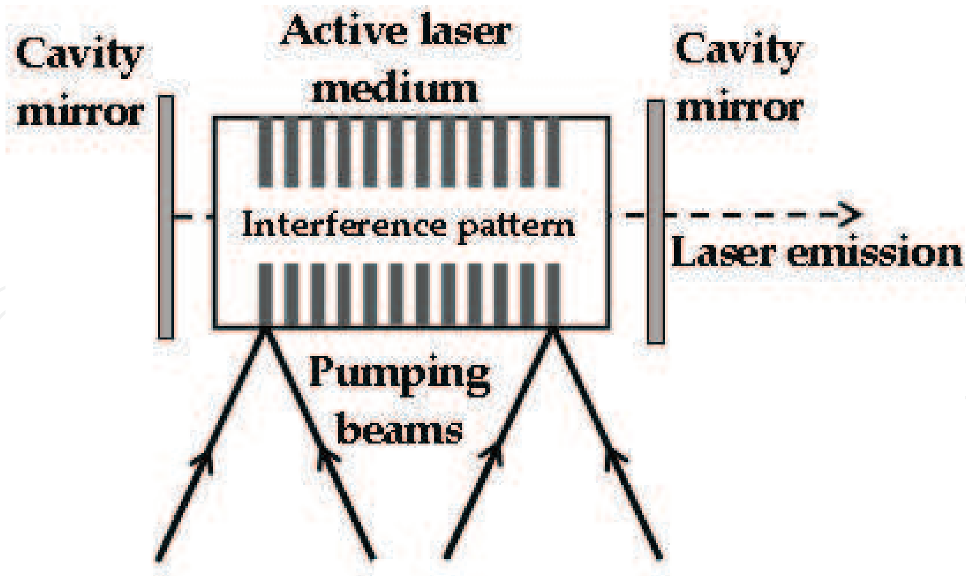

Figure 9. Dye laser with longitudinally distributed excitation.

In this part of chapter, the lasing from the dye-doped polymer film is investigated for the transversely distributed pumping (**Figure 10**). In this case, two mutually coherent pumping beams form in the active medium an interference pattern whose bright and dark strips are distributed perpendicular to the generated laser emission. The luminescent areas of the active medium inside of laser cavity of laser cell can generate laser emission separately. Due to correlation between the emitting centers of different lasing areas, the conditions for interference of the beams from these areas arise.

Therefore, the emission of such a laser should have spatial modulation and will form a pattern similar to the diffraction from the holographic grating. The aim of this study was to obtain and investigate the spatially modulated laser emission from a dye-doped polymer film and to get an improved pattern of lasing by improving the laser emission coherency as compared with DD CLC laser [21].

The experimental setup was the same as that used for holographic recording and for pumping of the DFB lasers which is shown above (**Figure 2**). The second harmonic (532 nm) of a Q-switched Nd:YAG laser with pulse duration of 15 ns was used for the coherent pumping. The repetition frequency of pulses was 12.5 Hz. The laser was ensured a coherence length of approximately 100 mm. With the beam splitter, the beam was divided into two beams of equal intensity. The beam splitter was composed of two interference mirrors 1 and 2 reflecting 50 and 100% accordingly. The distance between the mirrors (15–20 mm) ensured a stable interference pattern. The laser cell consisted of a polyvinyl alcohol (PVA) film doped with Rhodamine-6G and sandwiched between cavity mirrors enough transparent (≈75%) for the pumping emission. The total energy of the pumping radiation was 20–30 mJ, so the real effective energy of the pulse (i.e., the energy incident on the laser cell) was 14–20 mJ. The mirrors were placed with their reflective surfaces inward to the laser cell and by these surfaces have optical contact with the polymer layer. The radius of curvature of the concave mirror was 2 m. The pumping was carried out at the angles of the convergence of the pumping beams **0.6°**, **0.9°**, and **1.8°**. Concentration of the dye was 0.148% and the thickness of the polymer film was 130 μm. The pattern of the laser emission of this laser cell is shown in **Figure 11**. The photos **a, b,** and **c** correspond to the convergence angles of the pumping beams of **0.6°**, **0.9°**, and **1.8°**, respectively. As can be seen, along the cross section of the light bundle here, the smooth distribution of intensity typical for conventional lasers does not take place.

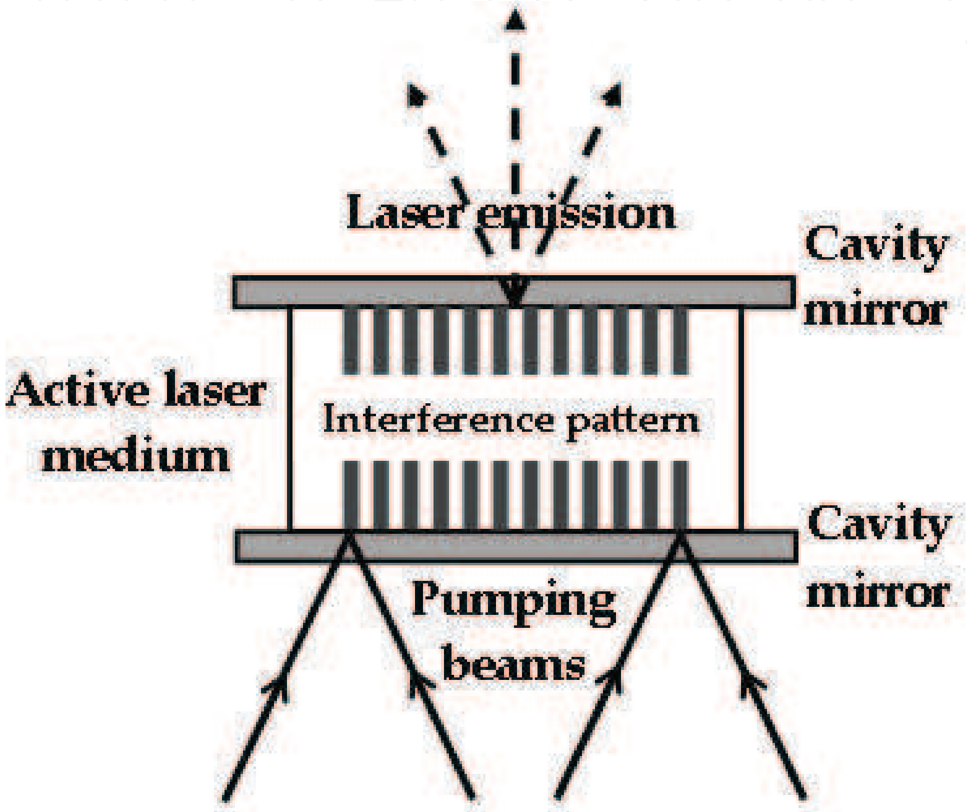

Figure 10. Dye laser with transversally distributed excitation.

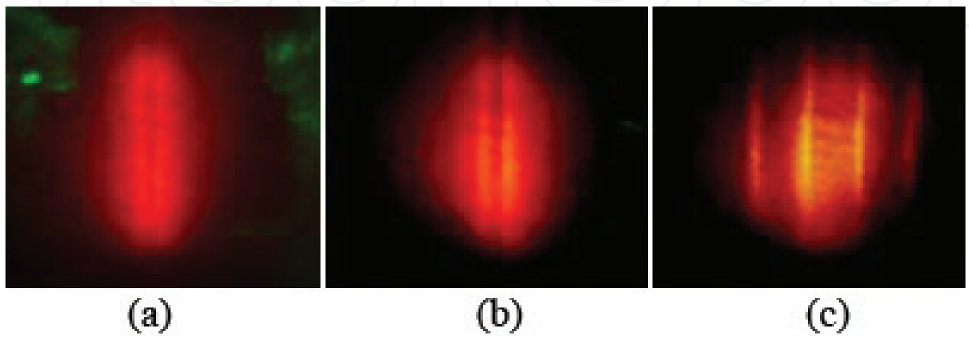

Figure 11. The emission pattern of the dye-doped polymer laser cell with the transverse distribution of the pumping at the convergence angles 0.6°, 0.9°, and 1.8° for the pumping beams—(a), (b), and (c).

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But the intensity has a spatially distributed form and qualitatively looks like a diffraction pattern from a diffraction grating. The angles between the intensity maximum directions correspond to the formula (3):

$$\varphi = 2\arcsin\left(\frac{\lambda_p}{2d}\right) \tag{3}$$

where, in our case, $\boldsymbol{\lambda}_{\mathrm{p}}$ is the wavelength of lasing and $\boldsymbol{d}$ is the period of the interference pattern of the pumping [4, 29, 30]. The diameter of the excited region was 1.5–2.0 mm. In this area, a sufficient number of the lines of interference pattern of the pumping, i.e., microlasers, were located. When shutting one of the pumping beams, the pattern of the spatial modulation, of the laser emission, disappears (**Figure 12**). The elongated shape of the emitted light field in all photos is a result of the plano-concave structure of the laser cavity. To avoid Fabry-Perot interference of the generated emission, the pumping was performed not at the central but at the peripheral part of the resonator.

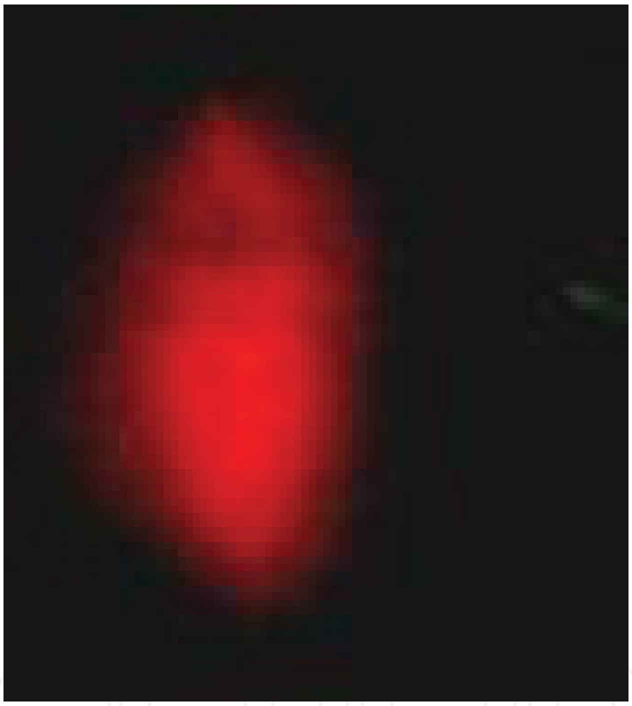

Figure 12. The emission pattern of the laser cell with single-beam pumping.

Because of pumping, the nonlinear effects can be induced in the polymer film. So the dynamic grating could be formed with enough modulation depth for observation of diffraction. To check this possibility, the area of lasing was tested with a beam of He-Ne laser (632 nm). But no signs of diffraction and, thus, no signs of any grating were detected.

The structure of the emitting spot was investigated under a microscope. In **Figure 13**, the photos of the spot demonstrating the modulated by intensity laser emission are shown. The convergence angles of the pumping beams were **0.6**°, **0.9**°, and **1.8**°, and spatial frequencies of emitting areas were **19, 28,** and **57** lines per millimeter accordingly.

As seen, the laser emission is observed from all the area of the pumping where the peaks of emission are allocated as microlaser stripes. Naturally, the peaks of lasing of these strips correspond to the intensity maximums of the interference pattern formed by the pumping beams.

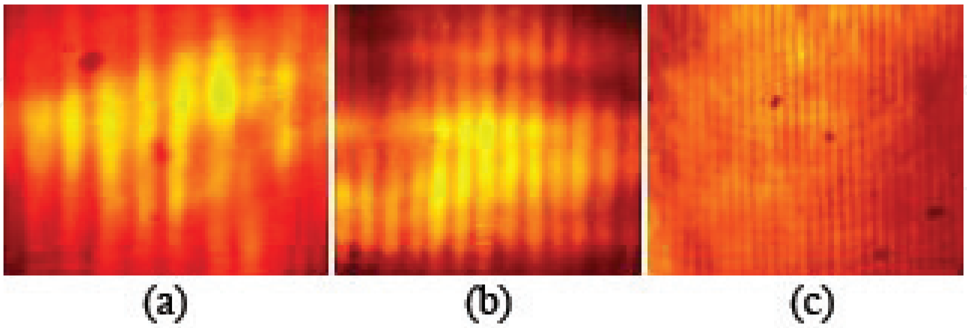

Figure 13. Microphotographs of the structure of the emitting area of the laser cell. The convergence angles of the pumping beams accordingly are (left to right) 0.6°, 0.9°, and 1.8°—(a), (b), and (c).

In **Figure 14**, the laser emission spectrum is shown. The spectrum along the cross section of the lasing of the radiation is strongly constant. The obtained spectrum of lasing is caused by the dye concentration, polymer matrix properties, and spectral reflection characteristics of the cavity mirrors.

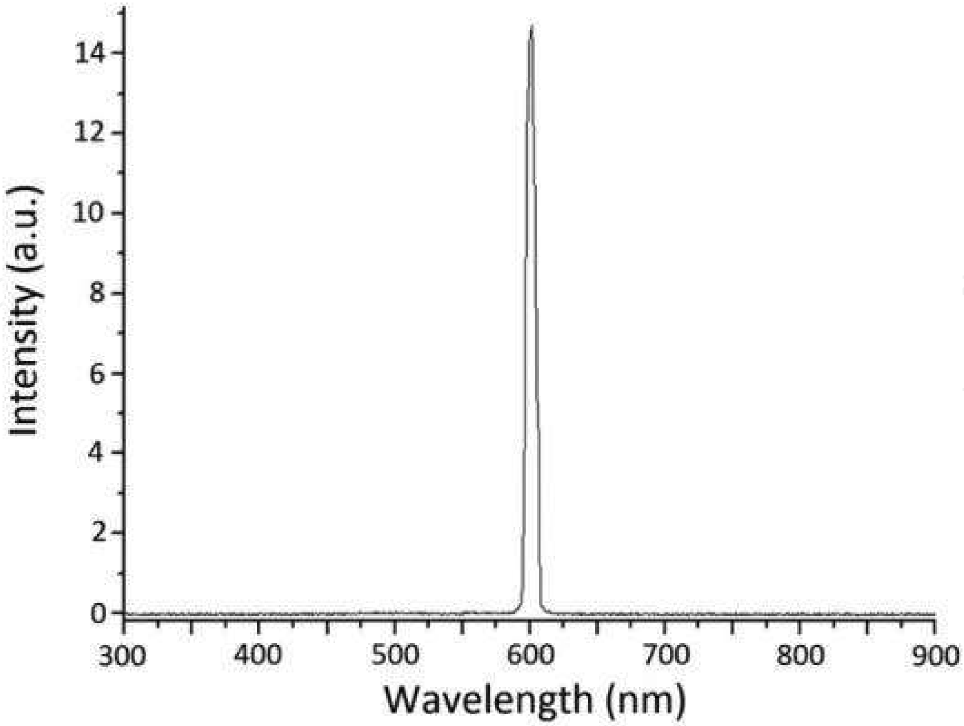

Figure 14. Spectrum of the laser emission.

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The aim of this study was realization of the laser with the transversely distributed pumping performed by double-beam coherent excitation of the dye-doped polymer film. According to the author's opinion, the emission field of such a laser should be spatially modulated and must carry information about the spatial distribution of the excitation field analogically described above DD CLC laser. The results shown in **Figure 10** confirmed these assumptions. By the opinion of the author, the emitted spot represented a one-dimensional array of mutually coherent microlasers which gives the interference field.

As it can be seen from **Figure 11**, the pictures of lasing do not contain the central maximum of intensity. There are observed only intensity maximums located symmetrically with respect to the pattern center. So the cross section of the laser emission is not quite similar to the diffraction. As it was noted above, the absence of such a diffraction grating was confirmed by the absence of any signs of diffraction when probing the lasing area with a beam of He-Ne laser (632 nm). By the interference of the coherent microsheaves, symmetrically located intensity maximums were formed. Therefore, we can say that the obtained pattern of emission is not a result of diffraction from a nonlinear grating formed in the active medium. The observed spatial modulation of lasing could be only the result of the interference of the mutually coherent microlaser emission. Thus, during the collective lasing of all strips, according to the Huygens-Fresnel principle [29, 30], the interference pattern shown in **Figure 11** was formed. The obtained laser emission carries information about the periodical distribution of the intensity of the pumping. Qualitatively it is almost similar to an elementary hologram whose diffraction orders also carry information about its periodical structure. So, we can say that the obtained laser operates like an active elementary dynamic hologram.

Thus, a dye-doped polymer film laser with transversely distributed excitation is investigated. Similar to the described DD CLC laser, the emission pattern of this laser is spatially modulated. However, the intensity maximums in this case are more visible due to the enhanced lasing conditions. The intensity distribution of laser emission contains information about the pumping interference field as it takes place in the case of elementary dynamic hologram. But unlike the passive diffraction of incident light, the pattern is formed due to the own radiation of the emitting areas.

According to future plans, the possibility of the reconstruction of the image of a two-dimensional transparent object on the basis of such approach will be investigated.

4. Conclusion

This work shows the possibility of creation of laser active holographic structures controlled by the transversely distributed optical pumping in dye-doped CLC and polymer layers. The obtained results confirm mutually coherency of the microlasers forming with the help of transversely distributed pumping. So laser radiation of such structures carries information about the spatial modulation of the pumping light field. Therefore laser active holographic structures resemble to corresponding usual holographic structures, but they are reconstructing information with the help of own laser radiation but not by diffraction of incident light.

On author's opinion, similar structures will reconstruct object images analogically to usual holograms and will create a basis for the development of new direction of optical information technologies.

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