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RING STRUCTURES IN RADIATION AT THE OUTPUT OF SOLID-STATE AND DYE LASERS WITH AN INTRA-CAVITY DIFFUSER

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Abstract

We observe transformations of radiation patterns with broadened rings at the output of Rh101 dye and Nd : YVO_4 lasers with Fabry–Perót (FP) cavities containing a cuvette diffuser with a mixture of LiF particles and isobutanol at changes in its state of immersion and in coherence of laser radiation. We compare the registered patterns with ring structures at the output of lasers with other sources of scattering in FP cavities. The mechanism of a low-coherence generation in a laser with an intra-cavity immersion diffuser is considered to explain the rearrangement of radiation patterns.

Keywords: Rh101 dye, Nd : YVO_4 lasers, Fabry–Perót resonator, immersion diffuser, radiation rings.

1. Introduction

Conical emission of thin concentric rings from a plano–plano (Fabry–Perót) laser cavity accompanying the main paraxial output beam is a known lasing feature, which has been already observed in the very first experiments with ruby and neodymium lasers; it was explained in a number of publications [1–8]. In fact, these interference rings display a function of the Fabry–Perót (FP) cavity transmission versus the angular coordinate. That is, the laser cavity itself acts as a FP etalon. Ring structures at the output of a short-cavity dye laser and an organic microcavity laser were later reported in [9, 10] and called Kastler rings, since they corresponded to the prediction of this kind of emission made by Kastler back in 1962 [2]. The short explanation of all these observations is as follows. The rings are formed as a result of interference of the coherent radiation of oscillating laser modes scattered by optical inhomogeneities inside the FP cavity [9].

In our experiments, we made new observations of ring structures at the output of a number of dye and solid-state lasers with an intra-cavity cuvette diffuser. A cuvette with a mixture of LiF microparticles and an immersion liquid (similar to the Christiansen filter) was installed in cavities of several dye lasers in order to control the coherence of their radiation [11,12]. In this paper, we discuss the features of radiation patterns with rings, which are observed at the output of the Rh101 dye and Nd : YVO_4 lasers with FP cavities containing an immersion diffuser or other sources of scattering. We present illustrations of the rearrangement of the output radiation patterns upon a change in the state of immersion in the cuvette

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diffuser, which is accompanied by changes in the degree of coherence of laser radiation in the cavity. The registered patterns are compared with the ring structures at the output of the laser without the cuvette diffuser. The mechanism of a low-coherence generation in a laser with an intra-cavity immersion diffuser that explains the rearrangement of radiation patterns is considered. The obtained data show that radiation patterns at the output of lasers with FP cavities can be used as indicators of the state of coherence of the laser radiation and also for estimations of the concentration of scattering centers and magnitudes of optical inhomogeneities in laser media.

2. Radiation Patterns with Concentric Rings at the Output of Rh101 Dye and $NdYVO_4$ Lasers with Fabry–Perót Resonators

A cuvette diffuser (gap, $l = 2$ mm) containing a dense mixture of LiF crystal granules (70 − 140 μm, refractive index $n = 1.39$) and an immersion liquid with the Rh101 dye dissolved was installed in plano-plano cavity with the length $L = 25$ mm; see Fig. 1 [12]. The reflection coefficients of the mirrors are: HR — $R_{532\ \mathrm{nm}} = 8.1\%$, $R_{598\ \mathrm{nm}} = 99.8\%$; OC — $R_{598\ \mathrm{nm}} = 62.7\%$.

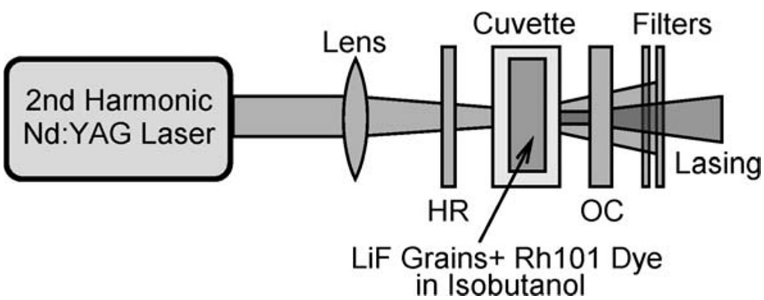

Fig. 1. Schematic of the experiment on lasing in a mixture of LiF particles (70 − 140 μm) with a solution of a Rh101 dye in isobutanol.

In Fig. 1, the Rh101 dye laser is pumped by 25 ns pulses of the second harmonic of a Nd : YAG laser with an energy of up to 17 mJ. The diameter of the focusing spot is ≈2 mm, and the pump intensity reaches $2 \cdot 10^7$ W/cm^2. The dye laser emits pulses at a wavelength near 598 nm (a spectrum width of 2 − 3 nm) with an energy of up to 1 mJ. At a high level of immersion (pure isobutanol at $T = 300$ K, $n = 1.39$), clear structures of rings with a bright central core are observed at the laser output; see Fig. 2 a. The divergence of the central region of the beam is 5.2 mrad, and the divergences (full angle) of the first 4 rings are 11.4, 16.0, 19.6, and 22.6 mrad. The positions of the rings along the angular coordinate correspond to the transmission maxima of the FP interferometer (FPI) formed by cavity mirrors; see Fig. 2 b.

The transmittance maxima of the FPI for a diverging beam at a wavelength λ correspond (as is well known) to the directions, for which the optical path length in the interferometer differs by an integer number of wavelengths $n\lambda$; $n = 1, 2 \ldots$, according to the relation [12]:

$$I = I_0 \frac{T^2}{(1-R)^2} \left[1 + \frac{4R}{(1-R)^2} \sin^2 \left(\frac{2\pi L \cos(\theta/2)}{\lambda} + \phi \right) \right]^{-1}, \qquad (1)$$

where I_0 is the intensity of the radiation incident on the FPI, I is the transmitted intensity, θ is the angle of incidence of the radiation, R is the average reflection coefficient of the mirrors, T is the transmittance, L is the FPI base (cavity length), and ϕ is the phase. So, the observed rings are obviously the result of

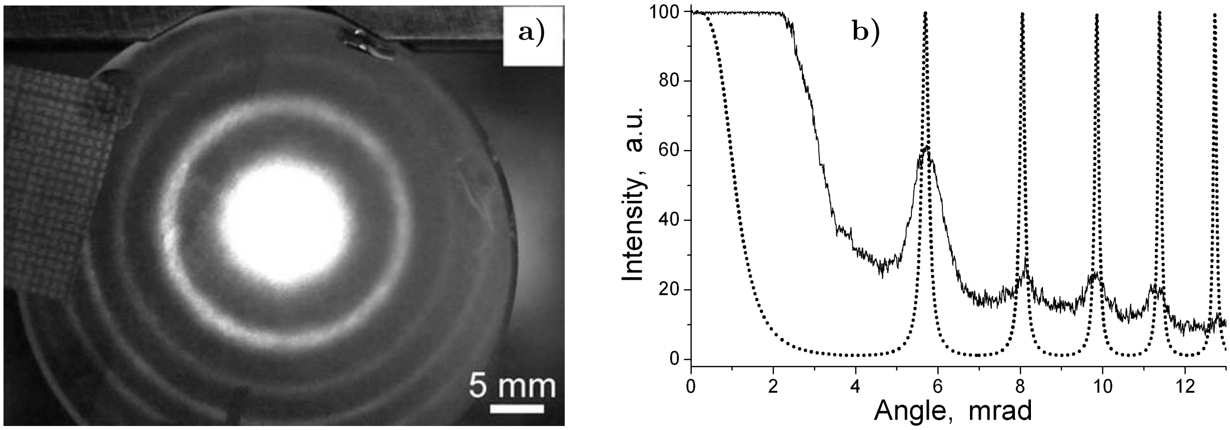

Fig. 2. Far field of the Rh101 dye laser output (a) with a ring structure obtained at a temperature near 300 K; here, focus of the lens $f = 2$ m. Intensity maxima of the ring structure at the Rh101 dye laser output (b, the solid curve) and the transmission maxima of the FPI formed by the mirrors (b, the dotted curve).

the interference of coherent radiation in the FP cavity and are similar to the ring structures observed and discussed in [1–10].

The state of immersion in the cuvette could be changed by varying the temperature or composition of the liquid. When the temperature in the cuvette was changed from 300 K to 295 K, the refractive index of isobutanol increased, while the LiF index practically did not change, that is, the immersion level in the cuvette was lowered. In this case, a beam with a smooth bell-shaped profile without rings was observed at the output of the Rh101 dye laser; see Fig. 3 a. Experiments with a two-slit Young interferometer showed a low degree of spatial coherence of the laser radiation, with $\gamma < 0.1$ in this case. Then, step-by-step, the level of immersion in the cuvette was gradually increased (by adding drops of ethanol, $n = 1.36$), broadened rings started to appear; see Fig. 3 b, c, and their width consistently decreased, and contrast increased to the state shown in Fig. 3 d, similar to that observed at 300 K with pure isobutanol.

To control the coherence in the laser based on a 3×3×2 mm^3 slab of an a-cut $Nd:YVO_4$ crystal with plane-parallel facets (1% activator concentration), we applied a cuvette diffuser (gap, $l = 1$ mm) with a similar mixture of LiF microparticles and isobutanol. The active element and the cuvette were installed in a cavity with a length $L = 13$ mm; see Fig. 4.

Scheme of $Nd:YVO_4$ laser with a cuvette diffuser is shown in Fig. 4; here, a mirror M1 with ≈100% reflectance at wavelength $\lambda = 1,064$ nm and ≈ 95% transmission for the pump radiation ($\lambda = 808$ nm) is deposited on one end of the active element and an antireflection coating is applied to the other end. The cuvette is placed near the flat output mirror M2, with 4% transmission at $\lambda = 1,064$ nm. CW LD end pumping of the active element is performed. To obtain ≈1 ms pump pulses with power of up to 100 W at a repetition rate of ≈10 Hz, a mechanical chopper of the LD radiation is used. A gain channel with a diameter of up to 1 mm is formed in the active element.

The experiments were carried out in a room with thermal control at a temperature near 25°C. The temporal structure of the $Nd:YVO_4$ laser was ≈1 ms pulses with a power from 10 mW (for a laser with a diffuser) to 1 W (without a diffuser). The width of the laser spectrum near $\lambda \approx 1,064$ nm was ≈1 nm. The laser beam profiles were recorded using a Thorlabs BC106-VIS CCD camera (6.6×8.8 mm registration window). In the absence of the cuvette, Gaussian mode lasing was observed with a divergence of ≈3 mrad. When a cuvette with a mixture of LiF particles and isobutanol was placed in the cavity and ethanol was added to the mixture, the radiation pattern at the laser output changed. For mixtures

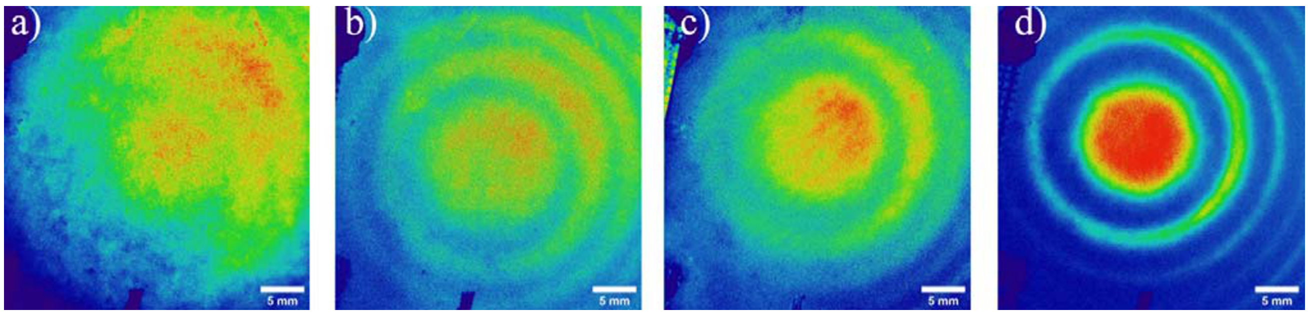

Fig. 3. Profiles of Rh101 dye laser beams in the far field (using a lens, $f = 2.1$ m) at different states of immersion in the cuvette diffuser. The experiments were carried out at $T \approx 295$ K with pure isobutanol (a), and with isobutanol containing incremental ethanol additions (b, c, d).

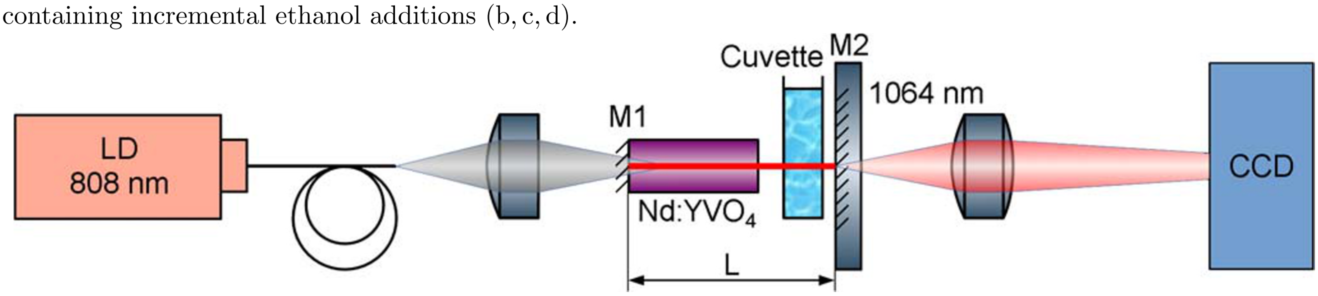

Fig. 4. Scheme of a Nd : YVO_4 laser with a cuvette diffuser; here, mirrors (M1 and M2), the pump module (LD), and camera (CCD).

with pure isobutanol or with a small admixture of ethanol (1 − 3 drops), an intense central generation region (core) and the structure of concentric rings surrounding this core were observed both in the near and far fields; see Fig. 5 a. The central region is overexposed in Fig. 5 a. The divergence of the central region is ≈5 mrad, and for the rings at the beam periphery, the divergence exceeds 30 mrad. The ratio of intensities at the maxima of the first ring and the core in the radiation pattern of the Nd : YVO_4 laser with the diffuser shown in Fig. 5 a is about 0.03. The positions of the maxima of the ring structure and the transmission maxima of the FPI formed by the plane mirrors of the cavity show the coincidence of the angular coordinates; see Fig. 5 b.

The dependence of the cavity transmission on the angular coordinate was calculated for specific parameters of the Nd : YVO_4 laser, in view of relation (1). The observed output radiation pattern thus indicates the propagation of scattered coherent radiation at certain angles to the resonator axis, with formation of a ring structure along the directions of the FP cavity transmission maxima due to interference. In this case, the measured degree of spatial coherence of the laser radiation is $\gamma \approx 0.7$. With further increase in the proportion of ethanol in the mixture (up to 10 drops) and a decrease of immersion, the ring structure in the beam profile disappears. The smoothed beam profile in the near field is illustrated in Fig. 5 c. The divergence of the radiation at the periphery of the Nd : YVO_4 laser beam for cuvettes with a low level of immersion reached 0.1 rad, and the laser pulse power was 10 − 20 mW. The disappearance of the rings indicates a decrease in the degree of coherence of the Nd : YVO_4 laser radiation. Since the emission spectrum remains narrow (≈1 nm), the observed effect should be associated with a decrease in the spatial coherence of the radiation. A decrease to values $\gamma \approx 0.18$ was observed.

In the absence of a cuvette diffuser in the FP cavity, we found at several overexposed CCD frames of the Nd : YVO_4 laser radiation patterns, that hardly visible structures of thin rings accompanied single-mode lasing, with the intensity of the first ring being at a level of $< 0.1\%$ of the central maximum; see

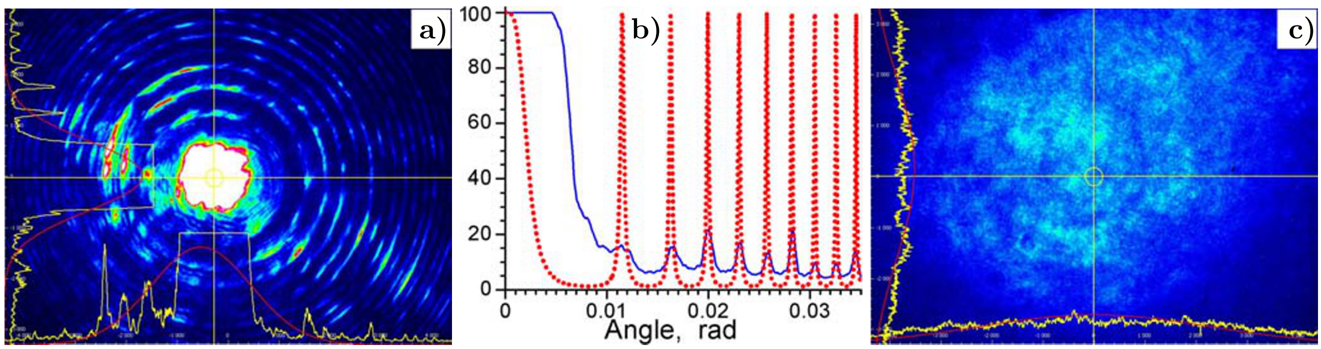

Fig. 5. Beam profile of a Nd : YVO_4 laser with a cuvette diffuser (1 mm gap, LiF/isobutanol) in the far field (using a lens, $f = 10.8$ cm) (a). Intensity maxima of the ring structure at the laser output (the solid curve) and the transmission maxima of the FPI formed by the cavity mirrors (the dotted curve) (b). Beam profile of the Nd : YVO_4 laser with a cuvette diffuser (LiF/isobutanol + 10 drops of ethanol) in the near field (7× magnification) (c).

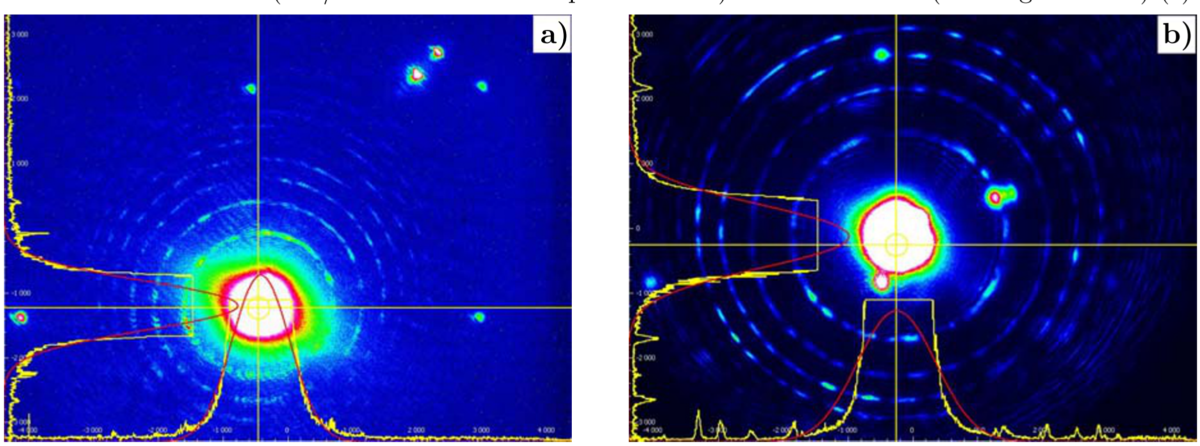

Fig. 6. Radiation patterns of the Nd : YVO_4 laser without a cuvette diffuser in the far field; here, only a $3{\times}3{\times}2$ mm^3 Nd : YVO_4 slab in the resonator (a) and the same slab and a ceramic plate in the resonator (b). The central region is overexposed; the ratio of intensities at the maximum of the first ring and the core are $< 0.1\%$ (a) and 0.6% (b).

Fig. 6 a. The angular coordinates of these rings correspond exactly to the parameters of the Nd : YVO_4 laser resonator. Ring structures were also observed when various laser optics elements were installed in the cavity instead of the cuvette diffuser. For example, for polished laser ceramic plane-parallel plates with a thickness ∼2 mm and different porosity, structures with an intensity of the first ring of 0.3–0.6% were observed; they are shown in Fig. 6 b.

3. Discussion of Experimental Results

Our observations of thin ring structures in the absence of a cuvette diffuser in the resonator of the Nd : YVO_4 laser directly correspond to the observations of similar structures at the output of ruby and neodymium lasers [1, 3–7]. These structures are associated with the properties of the FP laser cavity, where coherent laser radiation is scattered. In the Nd : YVO_4 and dye lasers, with an immersion diffuser and with changes in the immersion level, it is possible to observe the broadening of the ring structures up to the complete blurring of the gaps between the adjacent orders; see Figs. 3 and 5 c. As shown by our measurements, this process is accompanied by a decrease in the degree of coherence of the laser radiation. The obtained data provide a means to propose the following mechanism of generation in a laser with a FP cavity and an immersion diffuser at various levels of immersion, which explains the rearrangement of the radiation patterns. Below a phenomenological model for the case of narrow-band radiation is presented.

At a high level of immersion in the cuvette diffuser, the variations in the optical thickness ΔS of the medium are small across the beam cross section and a slightly distorted fundamental mode can arise, forming the generation core, which may be somewhat broadened compared to the case of the generation without a diffuser. The output radiation pattern with rings is similar to the pattern observed in the absence of a cuvette diffuser; compare Figs. 5 a and 6 a, b. In this case, coherent laser radiation interferes upon scattering in the cavity. Therefore, it is quenched along the directions near the FP transmission minima and enhanced along the directions of the FP transmission maxima. The rings are thin, and the background radiation between the rings is weak; see Figs. 2, 3 d, and 5 a.

At very low immersion, the variations in the optical thickness ΔS of the medium are significant across the beam. Due to the radiation refraction at numerous interfaces between particles and liquid and chaotic deflection of small parts of the beam, independent generation channels with small cross-sections differing in the optical length appear in the cavity. The mutual spatial coherence of such generation channels is obviously broken. As experiments have shown [12], even closely spaced (at a distance $\approx$100 μm) channels are incoherent. All these channels form a common spatially incoherent generation core with a smooth profile. Since radiation of very low coherence from this core circulates in the cavity, it does not interfere upon scattering and spreads at the laser output in the directions of maxima or minima of the FP cavity transmission and in the intermediate directions, without attenuation. In this way, a smoothed common laser beam profile with a large angular divergence is formed; see Figs. 3 a and 5 c. There are no rings in this case.

With an intermediate level of immersion, it can be assumed that, among the many generation channels, there are a number of rather large lasing regions with moderate variations in the optical thickness ΔS, which allow the development of coherent generation. Emission from one such region forms a concentric ring structure at the laser output, which is shifted in angular coordinate from the original location of the ring structure formed at a high level of immersion due to the shift in optical thickness S. Several such lasing regions with slightly different S and different angular coordinates create a structure with broadened rings; see Fig. 3 b, c. The gaps between the rings are filled with incoherent background radiation from the rest of the generation channels in the mixture. One can say that, in this case, we are dealing with partially coherent radiation at the laser output. With a further decrease in the level of immersion, the fraction of the coherent component decreases and low-coherence radiation fills the entire laser aperture.

We evaluated the difference in refractive indices of isobutanol, $n_{\rm iso}$, and LiF granules, $n_{\rm LiF}$, for the case, where the interference rings at the output of the FP cavity with a diffuser was broadened so much that they merged into a continuous background. In the evaluation, we assumed that the continuous background was formed when the rings from two certain generation channels in the FP cavity with interference order indices m and $m+1$ propagated at the same angle. In the evaluation, we took into account the random arrangement of N particles along the trajectory of the generation channel. In the case of the Rh101 laser, $\lambda = 6 \cdot 10^{-5}$ cm, $l = 0.2$ cm, and $N \approx 20$, we have $n_{\rm iso} - n_{\rm LiF} \approx 1.5 \cdot 10^{-3}$. With such a difference in the refractive indices of the liquid and granules, the rings should be blurred. Experimentally, we observed the disappearance of the rings with a change in temperature from 300 K to 295 K; see Figs. 2 and 3 a. While the change in $n_{\rm LiF}$ is negligible, in this case, $\Delta n_{\rm iso} = 2 \cdot 10^{-3}$ [12], which corresponds to the estimate. Taking into account the filling factor of the layer, the change in the optical thickness will be $\Delta S \leq 3\lambda$.

The above phenomenological model qualitatively explains the experimentally registered laser radiation patterns presented in Figs. 2, 3, and 5. Thus, we can qualitatively give the following characteristics of the radiation patterns observed at the output of the lasers with the FP cavity containing an immersion diffuser. Structures with thin concentric rings correspond to laser radiation of high coherence, smooth profiles without rings and with high radiation divergence correspond to practically incoherent output, and structures with broadened rings correspond to partially coherent laser radiation. In the absence of an immersion diffuser in the cavity, we observed structures consisting of thin rings typical of coherent radiation; see Fig. 6.

The ratio of the energy in the rings to the energy in the central maximum of the laser beam for dye lasers with an immersion diffuser may reach 20% [11]. The data obtained with the Nd : YVO_4 laser show that even in the absence of a cuvette diffuser in the cavity, it is possible to detect (at an intensity of $< 0.1\%$ from the central core) ring structures formed by coherent radiation. Such structures can serve as an indicator of the presence of scattering centers in the laser medium itself; see Fig. 6 a, or in other optical components of the resonator; see Fig. 6 b. By registering the intensity of such hardly visible rings, one can judge the concentration of scatterers. This assumption requires an additional separate study.

4. Conclusions

In this paper, we reported the observation of concentric rings structures at the output of Rh101 dye and Nd : YVO_4 lasers with FP cavities and an intra-cavity immersion diffuser. A cuvette with a dense mixture of LiF crystal particles (70 – 140 μm) and isobutanol (similar to the Christiansen filter) was used as the diffuser. The transformations of the radiation patterns with broadened rings at changes of the state of immersion in the mixture, accompanied by a change in the degree of coherence of the laser radiation were observed. We considered the mechanism of low-coherence generation in a laser with an intra-cavity immersion diffuser to explain the rearrangement of the radiation patterns. We compared the registered radiation patterns with similar structures in the radiation of lasers with FP cavities having other scattering sources. The data obtained show that output radiation patterns of lasers with FP cavities can be used as indicators of the state of coherence of laser radiation and also for estimations of the concentration of scattering centers and optical inhomogeneities in laser media.

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