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Absence of the laser output response to modulation of the optical density of the intracavity absorber

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Abstract. It is found that a laser with an anisotropic cavity containing an absorbing medium may exhibit no response of the output radiation intensity to the modulation of the optical density of the absorbing medium in the presence of a magnetic field. The conditions when this effect may be observed are determined, and its possible applications are briefly discussed.

1. Introduction

The introduction of an absorbing medium into a laser cavity typically results in a significant modification of the energy, spectral and temporal characteristics of the generated radiation. In the simplest case, this effect consists in a reduction in the output power at the absorption frequencies, which constitutes the basis of the intracavity laser spectroscopy (ICLS) methods [1]. In the case of selective absorption, one can observe under certain conditions the effect of the so-called spectral condensation – an increase in the radiation intensity – in the wings of the absorption band [2 – 4]. The introduction of a saturable nonselective absorber into the cavity may lead to a large number of effects: mode locking [5], pulsed Q-switching [6], or chaos [7].

The lasers with anisotropic cavities containing absorbing medium are of particular interest since there is a possibility to control the properties of their radiation, which is important, for example, in spectroscopic applications [8]. Up to now, the two limiting cases have been investigated in detail [9]: (1) The anisotropy of the absorbing medium adds to the anisotropy of the cavity, resulting in a greater total anisotropy of the laser, which may improve the resolution of the ICLS method and provide an opportunity to study various polarisation effects. (2) The medium anisotropy and the cavity anisotropy have the opposite signs, which may lead to an increase in the laser Q-factor at the absorption frequencies; this effect can be used to select the frequency of generation in a region of atomic transitions (see, e.g., Ref. [10]). If the optical density of the absorber is sufficiently large, these two limiting cases may combine. In the selective case, this leads to the appearance of wide absorption holes containing narrow emission peaks in the spectrum of the output radiation [9].

When the absorbing medium represents an atomic gas, the anisotropy is usually induced by the external magnetic field. The properties of lasers with such absorbers have been considered in detail only upon small variations of the applied magnetic field about the predefined standard values, according to the initial statement of the problem. We have investigated the influence of the intracavity absorber on the properties of the output radiation when the magnetic field strength was varied in a wide range. The experiments yielded a seemingly paradoxical result: under certain conditions, the laser output is independent of the presence of the absorbing medium inside the cavity.

2. Experimental studies

We performed the experiment using a helium-neon laser emitting at 1.15 μm. Fig. 1 shows the schematic of the laser cavity. The cavity was 72 cm long. The mirror *5* was totally reflecting. The output mirror *6* with a reflectivity of 0.964 served as well as one of the windows of the gas-discharge cell *2*, which had a discharge gap of 5 cm and was filled by neon at the pressure 0.32 kPa. The discharge current of the cell amounted to 72 mA. The cell was positioned inside a solenoid that created a uniform longitudinal magnetic field inside the absorbing medium. A plane-parallel plate *3* with a thickness of 2.4 mm was oriented at the Brewster angle with respect to the cavity axis; it served at once as the second window of the gas-discharge cell and as a partial polariser *3*. The amplitude transmissions p_1 and p_2 along the principal axes of this polariser was 1 and 0.88, respectively. As an active medium, a helium-neon cell with a discharge gap of 25 cm and perpendicular antireflection-coated windows was used. The discharge current in this cell was 14 mA.

The nonselective Faraday element *4* made of MOS-31 magnetooptic glass (the Verdet constant of $\beta = 0.04$ ang.min $\mathrm{Oe^{-1}cm^{-1}}$) was 10 cm long, and had antireflection-coated

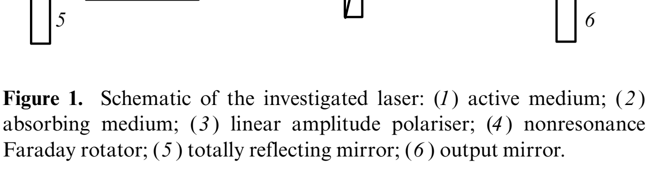

Figure 1. Schematic of the investigated laser: (*1*) active medium; (*2*) absorbing medium; (*3*) linear amplitude polariser; (*4*) nonresonance Faraday rotator; (*5*) totally reflecting mirror; (*6*) output mirror.

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ends. Placed inside the solenoid, this element rotated the polarisation plane of the radiation by the angle $\varphi = 0.05$ rad, thus producing circular phase anisotropy of the cavity. Note that the layout shown in Fig. 1 is not optimal for selecting the generated frequencies [10] because the Faraday element and absorbing medium are optically connected via a partial polariser rather than directly. We preferred this layout because we had to use the Brewster window in the gas-discharge cell to reduce the nonselective cavity losses. This allowed us to obtain stable generation under the conditions when the active medium amplification was relatively weak and there were several additional elements placed inside the cavity. As for the mentioned frequency selection, it can be efficiently realised if the polariser is placed at points A or O on the cavity axis (Fig. 1), or between the active medium and the Faraday element.

We studied the response of the generated power to the modulation of the absorber optical density. The modulation was produced by applying a constant voltage of 1000 V and alternate voltage with the amplitude 250 V and the frequency 50 Hz to the cell electrodes. We used low modulation frequencies so that the parameters of the output radiation could follow the variation in the intracavity losses.

The intensity of the output radiation was measured by the photomultiplier; a computer processed the variable component of its signal. This scheme allowed us to significantly suppress the noise at the frequency of the registered signal, as well as the low-frequency noise related to the mechanical instability of the cavity and its elements.

Fig. 2 shows the experimental results. When the magnetic field inside the absorber was zero and the Faraday element was switched off, the output intensity varied in the antiphase with respect to the optical density of the absorber (Fig. 2a). When a magnetic field was applied and the Faraday rotator turned on, typically both the constant and the alternate component of the output signal decreased. The former was determined, among other factors, by the angle of rotation of the polarisation plane in the rotator, while the latter was determined by the variation in the parameters of the absorbing medium, including the circular phase anisotropy, due to the modulation of the optical density. The both components depended on the magnitude and the sign of the magnetic field strength H inside the absorber. (We assumed H to be negative when the direction of optical rotation in the absorber and the Faraday element was the same.) For negative H, the relative modulation depth (the ratio of the amplitudes of the alternate and constant components of the output radiation) was greater than for $H = 0$, which agrees with the data of Ref. [11] where an increase in the sensitivity of the ICLS method was observed under the same conditions.

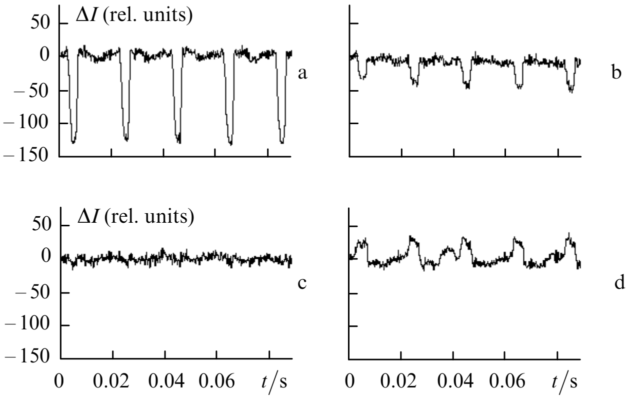

Figure 2. Oscillograms of the alternate component of the output radiation intensity ΔI upon modulation of the optical density of the absorber with the Faraday element on (a) and off (b–d). The strength of the magnetic field in the absorber was $H = 0$ (a), −340 (b), 300 (c), and 340 Oe (d).

The output radiation was modulated in the antiphase with respect to variation in the optical density of the absorber (see Fig. 2b) in a wide range of the strengths H (from negative values to $H \approx 300$ Oe). The modulation depth decreased with increasing H. For $H = 300$ Oe, the modulation of the output signal disappeared altogether (Fig. 2c). This effect did not depend on the degree of the optical density modulation: the output intensity remained the same even after the current in the gas-discharge was switched off. A further increase in H resulted in the appearance of the intensity modulation; however, its phase then coincided with the phase of variation in the optical density of the absorber (Fig. 2d).

The absence of the output signal modulation at $H = 300$ Oe means that the laser did not respond to the presence of the absorber inside the cavity. To explain this fact, we need to study in detail the contributions of absorption and optical rotation to the selective intracavity losses under various conditions.

3. Theoretical treatment

Consider the laser whose schematic is shown in Fig. 1. The cavity has a linear amplitude anisotropy and a circular phase anisotropy, induced by the polariser and the Faraday element, respectively. The longitudinal magnetic field induces the circular phase anisotropy and the amplitude anisotropy in the absorbing medium, which leads to resonant optical rotation and circular dichroism. The latter effect takes place at the off-centre frequencies of the absorption line. Such lasers can be conveniently analysed using the Jones matrix approach [8]. For the helium-neon laser used in the experiment, the high-Q cavity approximation is well justified, i.e., we can assume that the absorbing and active media only slightly change the transmission of the empty cavity (which does not contain these media). In this case, the intensity of the output radiation is given by [11]

$$I \sim E^2 = \frac{G - k_{\mathrm{L}} - \Delta k}{\theta_{\mathrm{g}} + \theta}, \tag{1}$$

where G and θ_{g} are the unsaturated gain and the gain saturation parameter of the active medium, respectively;

$$\begin{aligned} k_{\mathrm{L}} = &-\ln\Big|\tfrac{1}{2}r_1 r_2\Big\{(1+p^2)\cos 2\varphi + \\ &+\big[(1-p^2)^2 - (1+p^2)^2\sin^2 2\varphi\big]^{1/2}\Big\}\Big| \end{aligned} \tag{2}$$

are the losses of the empty cavity; r_1, r_2 are the reflectivities of the cavity mirrors; p is the amplitude transmission of the polariser for a light wave polarised along one of its principal axes (we assume that the transmission along the other principal axis is unity); φ is the angle of optical rotation during a single passage through the Faraday element; Δk are the selective losses due to the presence of the absorbing medium; θ is the parameter describing saturation of the losses Δk. Expression (1) describes single-frequency stationary lasing.

The magnetic field H applied to the absorbing medium affects the output radiation intensity through the quantities Δk and θ; each of them being composed of two terms, one defined by the absorption, and the other one by the dispersion of the intracavity absorbing medium. For the normal Zeeman effect and homogeneous broadening of the absorption line, we have

$$\Delta k = \frac{k_0 l}{2}\left\{\left[\frac{1}{1+(\delta-\varDelta)^2}+\frac{1}{1+(\delta+\varDelta)^2}\right]\right.$$
$$\left.+L\left[\frac{\delta-\varDelta}{1+(\delta-\varDelta)^2}-\frac{\delta+\varDelta}{1+(\delta+\varDelta)^2}\right]\right\}, \tag{3}$$

$$\theta = -\frac{k_0 l}{4}\alpha\left\{\mathrm{Re}\left[\frac{\beta_{11}+\beta_{12}}{1-\mathrm{i}(\delta-\varDelta)}+\frac{\beta_{22}+\beta_{21}}{1-\mathrm{i}(\delta+\varDelta)}\right]\right.$$
$$\left.+L\,\mathrm{Im}\left[\frac{\beta_{11}+\beta_{12}}{1-\mathrm{i}(\delta-\varDelta)}-\frac{\beta_{22}+\beta_{21}}{1-\mathrm{i}(\delta+\varDelta)}\right]\right\}, \tag{4}$$

where $k_0 l$ is the optical density of the medium at the central transition frequency ω_0 for $H = 0$; $\delta = (\omega - \omega_0)/\gamma$ is the relative detuning of the laser frequency ω from the frequency ω_0; γ is the homogeneous width of the absorption line; $\varDelta = \mu_B g H/\gamma$ is the relative splitting of this line by the magnetic field; μ_B and g are the Bohr magneton and the Lande factor, respectively. In an analogy with the experiment, we will assume the splitting $\varDelta$ to be negative when the direction of optical rotation in the Faraday element and in the absorbing medium coincide, and to be positive if these directions are opposite. The coefficient α, which is proportional to the transition probability, describes nonlinearity of the absorption. For the considered $2s_2 - 2p_4$ transition in neon ($\lambda =$ 1.15 μm), the expressions for β_{ij} ($i,j = 1,2$) take the form [11]

$$\beta_{11} = \frac{92}{\gamma}\left[\frac{1}{1-\mathrm{i}(\delta-\varDelta)}+\frac{1}{1+\mathrm{i}(\delta-\varDelta)}\right],$$

$$\beta_{12} = \frac{22}{\gamma}\left\{\left[\frac{1}{1-\mathrm{i}(\delta+\varDelta)}+\frac{1}{1+\mathrm{i}(\delta+\varDelta)}\right]\right.$$
$$\left.+(1+2\mathrm{i}\varDelta)\left[\frac{1}{1-\mathrm{i}(\delta-\varDelta)}+\frac{1}{1+\mathrm{i}(\delta+\varDelta)}\right]\right\},$$

$$\beta_{21} = \frac{22}{\gamma}\left\{\left[\frac{1}{1-\mathrm{i}(\delta-\varDelta)}+\frac{1}{1+\mathrm{i}(\delta-\varDelta)}\right]\right. \tag{5}$$
$$\left.+(1-2\mathrm{i}\varDelta)\left[\frac{1}{1-\mathrm{i}(\delta+\varDelta)}+\frac{1}{1+\mathrm{i}(\delta-\varDelta)}\right]\right\},$$

$$\beta_{22} = \frac{92}{\gamma}\left[\frac{1}{1-\mathrm{i}(\delta+\varDelta)}+\frac{1}{1+\mathrm{i}(\delta+\varDelta)}\right].$$

The first term in expression (3) describes absorption by the medium at the laser frequency, the second one describes the losses due to resonant optical rotation in the absorbing medium. The saturation of these two effects is determined by the corresponding terms in equation (4). The parameter L, which characterises the increase in the angle of optical rotation at the absorption frequencies due to the intracavity effect, is defined by the expression

$$L = -\mathrm{Im}\frac{a_{11}^2 + a_{11}b}{\lambda_0 b}, \tag{6}$$

where a_{ij} and $\lambda_0 = \frac{1}{2}(a_{11} + a_{22} + b)$ are, respectively, the elements of the Jones matrix and the amplitude transmission of the laser cavity neglecting the effects of the active and absorbing media; and $b = \left[(a_{11} - a_{22})^2 + 4\,a_{12}a_{21}\right]^{1/2}$.

Note that the two components of the selective losses and the corresponding saturation parameter are proportional to the optical density of the medium. The first term in expression (3) (the absorption component) always has the same sign; it results in additional cavity losses. The second term in expression (3) (dispersive or polarisation component) may change its sign with a change in the sign of $\varDelta$, i.e., in the direction of the magnetic field; therefore, this term may either increase or decrease the cavity losses at the corresponding frequencies. The parameter θ behaves similarly. In the intracavity polarisation spectroscopy experiments, the magnetic field is such that the two components of Δk, i.e., the absorption one and the polarisation one, have the same sign and therefore are added up, leading to increased total losses. If the lasing frequency is locked to the atomic absorption line, these two terms have opposite signs and, as a result, the cavity Q-factor reaches its maximum at the absorption frequencies. Note that the total losses $k_L + \Delta k$ appearing in equation (1) cannot be negative for any values of the magnetic field and the parameters of the cavity and the absorbing medium, as follows from the analysis of expressions (2) and (3).

However, one can see from equation (3) that, for certain values of the cavity parameters (L), the laser frequency (δ), and the magnetic field strength ($\varDelta$), the total losses in the absorbing medium vanish ($\Delta k = 0$). This means that the intracavity absorbing medium ceases to affect the output radiation intensity. In particular, the output intensity remains constant if the optical density of the absorbing medium is modulated.

Fig. 3 shows the calculated dependence of the laser output on the harmonic modulation of the optical density of the absorber. We carried out the calculation for the point O shown in Fig. 1. The parameters used in the calculation were chosen to be as close as possible to the experimental ones: $G = 0.15$; $\theta_g = 12.975$ CGSE units; $k_0 l = 0.025$; $\gamma = 10^8\,\mathrm{s}^{-1}$; $\alpha = 3{\cdot}10^8$ CGSE units; $r_1 = 1$; $r_2 = 0.964$; $p = 0.88$; and $\varphi = 0.05$ rad.

For a moderately large negative absolute value of the relative splitting of the absorption line in a magnetic field ($-1 < \varDelta < 0$), the laser output decreases and the modulation depth increases (curve *2* in Fig. 3). This agrees with the experimental data of Ref. [11], where the sensitivity of the ICLS

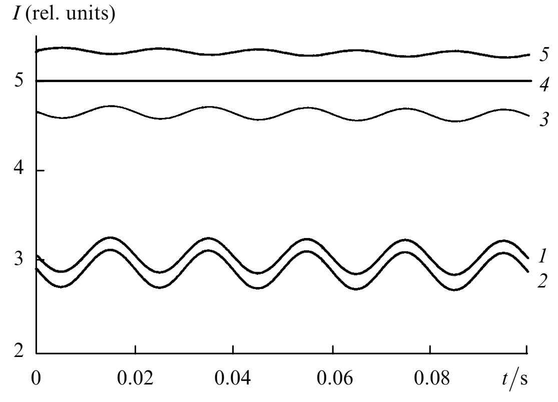

Figure 3. Calculated time dependences of the laser output intensity upon modulation of the optical density of the absorber; $\varDelta = 0$ (*1*), -1(*2*), 0.6 (*3*), 0.795 (*4*), and 1 (*5*); $\varphi = 0.05$.

method increased when the angles of optical rotation in the medium and in the Faraday rotator added. In our case, the sensitivity reaches its maximum at $\varDelta = -0.6$. Since the signs of the absorption and dispersive losses are the same in this region, the output radiation and the optical density of the medium are modulated in the opposite phases.

For positive splitting $\varDelta \sim 1$, the output radiation is modulated in phase with the optical density of the medium, its intensity being greater than that in the absence of the intracavity absorbing medium (curve *5* in Fig. 3) because the medium reduces the cavity losses at the absorption frequencies. This is a well-known effect; earlier it was used for selection of the generated frequencies [10].

The experimentally realised situation, when the output radiation intensity is independent of the modulation of the optical density of the absorber, corresponds to theoretical curve *4*, which was calculated for the splitting $\varDelta = 0.795$. As already noted, the essence of the observed effect consists in the fact that in the cavities with the special anisotropy properties the absorption-induced and dispersion-induced additions to the cavity *Q*-factor have equal magnitudes and opposite signs. This effect is independent of the optical density of the medium at the central frequency of the unsplit absorption line. Note that this effect is realised for sufficiently small optical densities of the medium, when expressions (3) and (4) are valid. In this case, both the energy and polarisation properties of the output radiation are independent of the medium. Fig. 4 shows the time dependences of the alternate component of the output radiation, which were calculated for the same conditions as in the experiment (see Fig. 2). Comparison of Fig. 4 and Fig. 2 shows that there is a good qualitative agreement between the developed theoretical model and the actual experiment.

Consider now the influence of the intrinsic cavity anisotropy on the modulation parameters of the output radiation intensity. In our calculations, we used the approximation of the linear polarisation of the generated wave, which imposes the following restriction on the relationship between the phase anisotropy and the amplitude anisotropy of the cavity:

$$|\varphi| \leqslant \frac{1}{2}\arcsin\left|\frac{1-p_2^2}{1+p_2^2}\right|. \tag{7}$$

The cavity parameters affect the polarisation component of the absorber-induced selective losses through the quantity L (see Eqns (3), (4), (6)), which is determined not only by the integral parameters of the cavity and the individual properties of the anisotropic elements, but also by the arrangement of these elements inside the cavity. Indeed, the expressions for the parameter L at the points O and A (see Fig. 1) do not coincide:

$$L_{\mathrm{O}} = \frac{2p_2\sin 2\varphi}{\left[(1-p_2^2)^2 - (1+p_2^2)^2\sin^2 2\varphi\right]^{1/2}}, \tag{8}$$

$$L_{\mathrm{A}} = \frac{(1+p_2^2)\sin 2\varphi}{\left[(1-p_2^2)^2 - (1+p_2^2)^2\sin^2 2\varphi\right]^{1/2}}. \tag{9}$$

The parameters L_{A} and L_{O} are the same only if the cavity is isotropic or it has only one type of anisotropy, either the amplitude anisotropy or the phase anisotropy. Otherwise, L_{A} and L_{O} are different, and the parameters Δk and θ do not coincide at the points A and O. This means, for example, that we can select such experimental conditions that the radiation coming out from one of the cavity mirrors is modulated, whereas the one coming out from the other mirror is not (Fig. 5a). Furthermore, for certain parameters of the cavity and absorbing medium, the beams coming out from the different cavity mirrors are modulated in the antiphase (Fig. 5b). This happens if for given values of p, φ, $\varDelta$ the absorption and the dispersive components of the medium-induced losses have the same sign, and if, for one of the points, O or A, the first component is dominant (the radiation intensity varies in the antiphase with respect to the optical density of the medium) whereas, for the other point, the second component is dominant (the modulations are inphase).

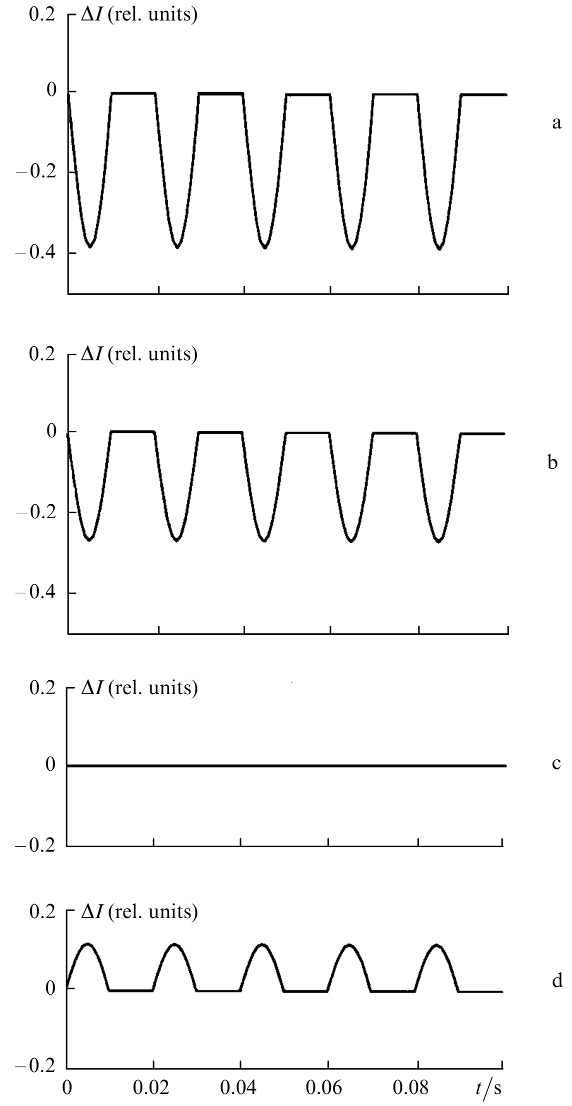

Figure 4. Calculated alternate component of the output intensity ΔI upon modulation of the optical density of the absorber; $\varDelta = 0$ (a), -2(b), 0.795 (c), and 2 (d); $\varphi = 0$ (a) and 0.05 rad (b – d).

The above theoretical treatment is based on the assumption of the homogeneous broadening of the absorption line and the normal Zeeman effect. However, our estimates show that, for other profiles of the spectral lines (Doppler or Voigt profiles) and the anomalous Zeeman effect, expressions (3), (4) have the same structure. Namely, each of these quantities consists of an absorption component and a polar-

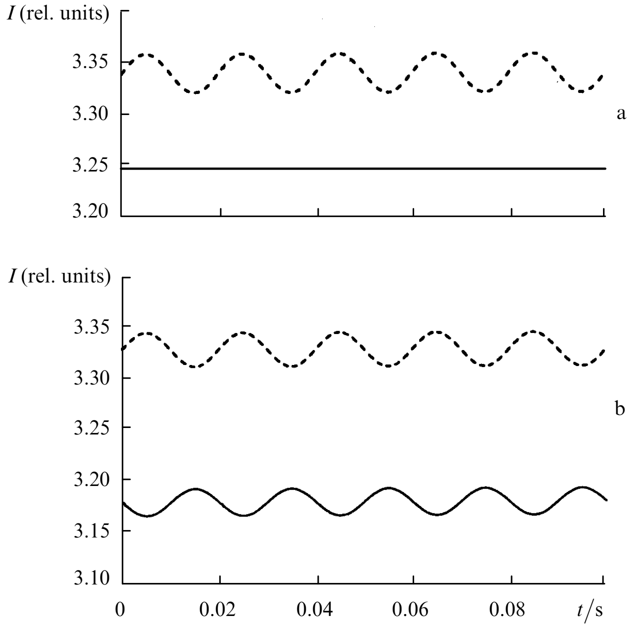

Figure 5. Influence of the modulation of the absorber optical density on the time dependence of the output radiation intensity at the points O (solid curve) and A (dashed curve) on the cavity axis (Fig. 1) for $\varDelta = 4.28$ (a) and 2.5(b), $p = 0.2$, and $\varphi = 0.25$ rad.

isation component, which are both proportional to the optical density of the absorber. These components may have opposite signs, and under certain conditions they cancel each other.

To conclude, we will briefly discuss the possible applications of the observed effect to the intracavity spectroscopic measurements. When there is no response of the output intensity to a modulation of the optical density of the absorbing medium, expression (3) for the central frequency of the unsplit Lorentzian absorption profile is transformed to the simple relationship

$$L\varDelta = 1. \tag{10}$$

For the Doppler-broadened absorption line of linewidth $\Delta\varDelta_{\mathrm{D}}$, expression (3) has the form

$$\int_{-\varDelta_1}^{\varDelta_1} \mathrm{e}^{t^2}\mathrm{d}t = \frac{\sqrt{\pi}}{L}, \tag{11}$$

where $\varDelta_1 = \mu_{\mathrm{B}} gH/(0.6\nu_{\mathrm{D}})$ is the relative splitting of the absorption profile in the magnetic field. Knowing L, which can be calculated from the parameters of the polariser and the Faraday element using expression (8), and measuring the magnetic field strength corresponding to the absence of modulation of the output signal, we can easily determine the width of the absorption band of the medium. The preliminary estimates based on the results of the above-described experiment give the value $\Delta\nu_{\mathrm{D}} \approx 1.6$ MHz for the neon line at 1.15 μm, which is in good agreement with the results of Ref. [12]. Elaboration of the measurement technique is a subject for separate investigations.

4. Conclusions

Thus, we have observed a novel property of the laser: the output radiation intensity does not respond to intracavity absorption of light at the laser frequencies. In particular, this is manifested in the absence of variation in the output intensity upon modulation of the optical density of the absor-ber. This effect can be observed in the cavities with complex anisotropy (the combined amplitude and phase anisotropy with different proper bases) or in the case of induced anisotropy of the absorbing medium (atomic gas) with a corres-ponding proper basis. A modulation of the optical density of the absorber can also result in the inphase modulation of the radiation coming out from one of the output mirrors and the antiphase modulation of the radiation coming out from the other mirror of the linear cavity.

The obtained results may find applications for controlling the properties of the laser radiation and in some spectroscopic problems: linewidth measurements, anisotropy detection, and measurements of the magnetooptical properties of gases.

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