Spectroscopy within the Doppler line with the aid of a ring laser

É. M. Belenov, M. V. Danileĭko, V. R. Kozubovskiĭ, A. P. Nedavniĭ, and M. T. Shpak

Physics Institute, Ukrainian Academy of Sciences
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We indicate the possibility of laser spectroscopy within the Doppler contour, without using directly the effect of Lamb hole burning of the Doppler line. We show that a ring laser is a more sensitive spectroscope than a laser with a Fabry–Perot resonator.

1. Nonlinear optical resonances of the output power of lasers make it possible at present to separate the spectral lines against the background of relatively broad Doppler contour, provided they are not masked by homogeneous broadening.[1] This resolution of the spectral line is based on the Lamb effect[2] of the burning of the Doppler line.

In this paper we point to a possibility of laser spectroscopy within the Doppler line without using the Lamb dips directly. This possibility is physically based on the competition between the effects of spectral and spatial saturation of the gas and of the phase interaction of the traveling waves of a ring laser (RL), which leads to resonances of the output power of the RL at the centers of the spectral components of the Doppler contour.

The experiments on resolving neighboring spectral components of an absorbing Ne line belonging to two isotopes Ne^{20} and Ne^{22} were performed with the aid of an He-Ne RL with $\lambda = 3.39\ \mu$. It is difficult to perform such an experiment with a Fabry-Perot resonator laser, because the absorption coefficient of the transition $5s'\,[1/2]_1 \to 4p'\,[3/2]_2$ in Ne is so small that it is impossible to resolve the fine structure of this line with the aid of the Lamb effect.

2. The system of equations[3] describing the time variation of the amplitudes $E_{1,2}$ and the phases $\Phi_{1,2}$ of the RL field, which is a superposition of two traveling waves

$$E(x,t) = E_1(t)\cos[\nu t - kx + \Phi_1(t)] + E_2(t)\cos[\nu t + kx + \Phi_2(t)]; \quad (1)$$

can be approximately reduced to the form

$$\dot{\Psi} = \frac{\nu}{Q}\, m \sin\Phi + \frac{\nu}{Q}\, p \sin\Psi\cos\Psi; \quad (2)$$

$$\dot{\Phi} = \frac{\nu}{Q}\cos\Psi\left(m\frac{\cos\Phi}{\sin\Psi} - \Delta\right);$$

by the substitution

$$E_1 = E_0\cos\frac{\Psi}{2}, \quad E_2 = E_0\sin\frac{\Psi}{2}. \quad (3)$$

In (2), $\Phi = \Phi_1 - \Phi_2$, m is the coefficient of the coupling between the waves produced as a result of the reflections by the inhomogeneities of the dielectric constant, Q is the quality factor of the resonator, and the parameters p and Δ are given by

$$p = \frac{1}{2}\sum_i \frac{a_i}{2}\left[\frac{\mu_i^2}{\mu_i^2 + \gamma_i^2} - \frac{\gamma_i\,\Gamma_i}{(ku)^2}\right]E_0^2;$$

$$\Delta = \frac{1}{2}\sum_i \frac{a_i}{2}\,\frac{\mu_i\,\gamma_i}{\mu_i^2 + \gamma_i^2}\,E_0^2; \quad (4)$$

where $\mu_i = \nu - \omega_i$ is the deviation of the RL lasing frequency from the natural frequency of the transition of the amplifying or absorbing gas; $a_i = e^2|r_i|^2/2\hbar^2\gamma_i\Gamma_i$ is the saturation parameter (r_i is the radius-vector matrix element); Γ, γ, and ku are the radiative, homogeneous, and Doppler linewidths; $E_0^2 \approx E_1^2(t) + E_2^2(t)$; the algebraic summation in (4) is over the number of components of the RL medium.

The stationary solution of the system (2)

$$\cos\Phi = -\frac{\Delta}{m}\sin\Psi, \qquad \sin\Phi = -\frac{p}{m}\sin\Psi\cos\Psi; \tag{5}$$

describes the generation of two traveling waves with different intensities. It is easy to obtain from (5) an expression for the dependence of the intensity $E_2^2 \sim \Psi^2$ of the weak RL wave on the generation frequency ν. Analysis shows that when the frequency deviation between the components of the Doppler line exceeds the homogeneous width, the quantity $E_2^2(\nu)$ has a system of extrema that fix the line transition frequencies.

In particular, for an RL with an amplifying medium and an absorbing medium having a fine structure, E_2^2 takes the form

$$E_2^2 = \frac{16m^2}{(a_{(-)}E_0)^2}\left\{\left[\gamma^{(+)}\frac{a_{(+)}x}{a_{(-)}x^2+\gamma^{(+)2}} + \frac{x+\frac{\delta}{2}}{\left(x+\frac{\delta}{2}\right)^2+1} + \frac{x-\frac{\delta}{2}}{\left(x-\frac{\delta}{2}\right)^2+1}\right]^2 + \left[\frac{a_{(+)}}{a_{(-)}}\left(\frac{x^2}{x^2+\gamma^{(+)2}} - 2\frac{\gamma^{(+)}\Gamma}{(ku)^2}\right) - \frac{\left(x+\frac{\delta}{2}\right)^2}{\left(x+\frac{\delta}{2}\right)^2+1} - \frac{\left(x-\frac{\delta}{2}\right)^2}{\left(x-\frac{\delta}{2}\right)^2+1}\right]^2\right\}^{-1} \tag{6}$$

where $\delta = |\omega_1^{(-)} - \omega_2^{(-)}|$ is the frequency spacing between the spectral components of the absorption line, and the frequency is reckoned from the center of the summary absorption contour $\nu = [\omega_1^{(-)} + \omega_2^{(-)}]/2 + x$ in dimensionless units (we put $\gamma^{(-)} = 1$). It follows from (6) that E_2^2 has three extrema that determine the frequencies $\omega^{(+)}$ of the amplifying gas and $\omega_1^{(-)}$ and $\omega_2^{(-)}$ of the absorbing gas. If it is assumed that $\gamma^{(+)} \gg \gamma^{(-1)}$, so that the extremum at $\nu = \omega^{(+)}$ cannot be noticed in a scale such as $|\nu - \omega^{(+)}| \sim \gamma^{(-)}$, then expression (6) for E_2^2 has two maxima at the centers of the absorption-line components. Figure 1 shows a plot of the wave intensity E_2^2 against the generation frequency x at different frequency spacings δ between the spectral components of the absorption line in the case $\gamma^+ \gg \gamma^-$. We see that at $\delta > \gamma^-$ the laser radiation has two power resonances, and at $\delta \leq \gamma^-$ the resonances merge into one.

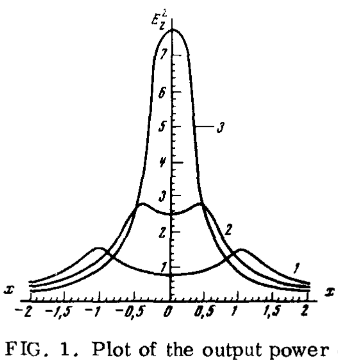

FIG. 1. Plot of the output power of one of the traveling waves of the RL against the generation frequency at different values of the parameter δ: 1 – $\delta = 2.5\gamma^{(-)}$; 2 – $\delta = 1.5\gamma^{(-)}$; 3 – $\delta = \gamma^{(-)}$.

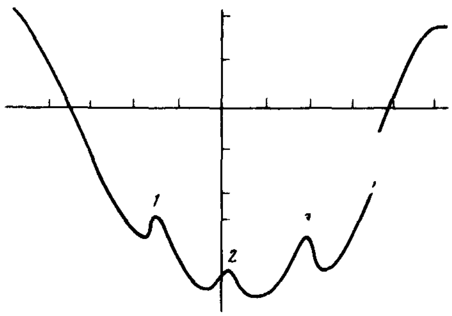

FIG. 2. Oscillograms of output power of one of the traveling waves of the RL against the generation frequency: 1-resonance at the center of the Ne^{22} absorption line at Ne^{22} pressure 0.5 Torr; 2-resonance at the center of the Ne^{20} gain line, He-Ne^{20} pressure 2.4 Torr; 3-resonance at the center of the Ne^{20} absorption line, Ne^{20} pressure 1 Torr.

3. We used in the experiment an He-Ne RL with $\lambda = 3.39\ \mu$. The length of the three-mirror resonator was $L = 1.1$ m, and that of the gas-discharge tube was $l = 25$ cm. The resonator contained two absorbing cells with Ne^{20} and Ne^{22}, the length of each cell being 20 cm. The Ne in the absorbing cells was excited with a high-frequency field. The opposing-wave coupling coefficient due to the reflections was regulated with the aid of a quartz plate placed in the resonator. In the region of one-wave lasing, we are able to observe the resonances of the RL power at the centers of the absorption lines of Ne^{22} and Ne^{20}. Figure 2 shows an oscillogram of the output power of one of the RL waves as the laser length is scanned. Curves 1 and 3 show the resonances at the centers of the Ne^{22} and Ne^{20} absorption lines, and 2 shows the resonance at the center of the gain line.

Since the scanned laser generation contour was determined by the intermode distance $\Delta = c/L = 270$ MHz, it is easy to determine the frequency interval between the structure components of the absorbing Ne line. In our case, $\delta = 84 \pm 2$ MHz.

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