CHANGE OF ABSORPTION LINE SHAPE AND OF DISPERSION OF A TWO-LEVEL SYSTEM IN A QUASIRESONANT MONOCHROMATIC RADIATION FIELD

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We investigate the change of shape of the Zeeman absorption line and of the dispersion of cadmium vapor under the influence of resonant and quasiresonant radiation. The theoretically predicted reversal of the sign of the absorption coefficient of a two-level system under the influence of a powerful monochromatic radiation without production of population inversion is confirmed.

We report here experiments on the change of the susceptibility of optically-oriented rarefield Cd^{113} vapor near the frequency of the Zeeman splitting of the ground state under the influence of a quasiresonant radiation field. The results of the experiments show that two-level systems without population inversion, to which a strong radiation field is applied, can be used to construct tunable stimulated-emission amplifiers and generators.

We used in the experiment one of the schemes considered in [1, 2] for optically orienting cadmium atoms in the presence of a buffer gas. The Cd^{113} atom in the ground state has an angular momentum I = 1/2, so that in a constant magnetic field H_z the ground state splits into two levels. The preferred population of one of these levels (orientation) was produced by illuminating the Cd^{113} vapor with a beam of 3261-Å resonant radiation from a lamp with Cd^{114}, placed in a local magnetic field ∿ 0.5 kOe. The experimental setup is shown in Fig. 1. A cell containing Cd^{113} vapor saturated at 220°C as well as a buffer gas (xenon, 100 Torr) was placed at the center of a system consisting of three pairs of Helmholtz coils producing mutually perpendicular magnetic fields, viz., constant field H_z = 5 Oe and two RF fields $H_x(t) = H_0\cos\omega_0 t$ (strong) and $H(t) = H\cos\omega t$ (weak), with a variable frequency ω. The orienting beam was directed in the YOZ plane at 45° to the Y and Z axes, and served simultaneously as the recording beam. As is well known [3], in such an arrangement the light beam becomes modulated after passing through the cell at the frequencies of the transverse component of the angular momentum resulting from the action of the alternating fields. A synchronous detector with a reference voltage of frequency ω was used to measure the light-modulation component at the frequency of the weak field $H_y(t)$. When ω is in the immediate vicinity of ω_0, a parasitic modulation signal of alternating sign and frequency ω_0 is observed and is not fully integrated by the filter of the synchronous detector.

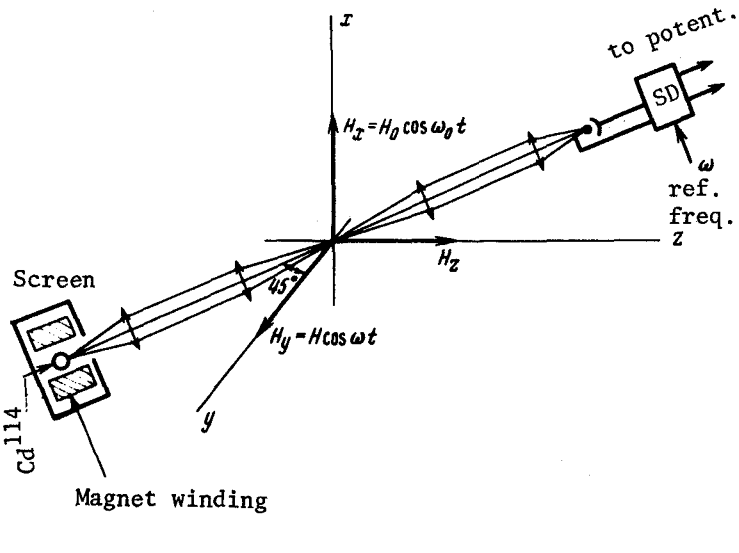

Fig. 1

Depending on the phase difference between the reference and the recording signals, we could measure either the real or the imaginary part of the polarization (i.e., of the susceptibility) of the cadmium vapor at the frequency ω. The Zeeman splitting frequency 4.7 kHz is smaller by many orders of magnitude than the frequencies of the transitions to the nearest levels, so that such a system can be regarded as a two-level system and one can investigate the variation of its susceptibility under the influence of a strong quasiresonant field in purest form. Figures 2 and 3 show the signals obtained by us, proportional to the imaginary part (i.e., to the extinction coefficient, Fig. 2) and to the real part (i.e., to the refractive index) of the susceptibility in case of exact resonance with the strong field, $\omega_0 = \omega_{21}$, and in the case of a deviation from resonance amounting to ∿ 1.6 of the line width $\gamma = 1.6$ Hz. We see that in the case of resonance, $\omega_0 = \omega_{21}$, the sign of the imaginary part of the susceptibility reverses in the region of frequencies ω close to ω_0, and the width of this region increases linearly with increasing strong-field amplitude H_0. This picture changes radically when ω_0 deviates from ω_{21} by an amount γ even in the case of quite large H_0, corresponding to a line splitting much larger than γ. In this case the absorption line is split by an amount proportional to H_0, and the signs of the split components differ and vary with the sign of $\mathcal{E}_0 = \omega_0 - \omega_{21}$ (Figs. 2d, c). It is curious that in the case of a nonresonant action of the strong field the width of the absorption sign-reversal region is approximately equal to the absorption width, and the maximum attainable gain decreases with increasing $\mathcal{E}_0$ like $\sim 1/\mathcal{E}_0$.

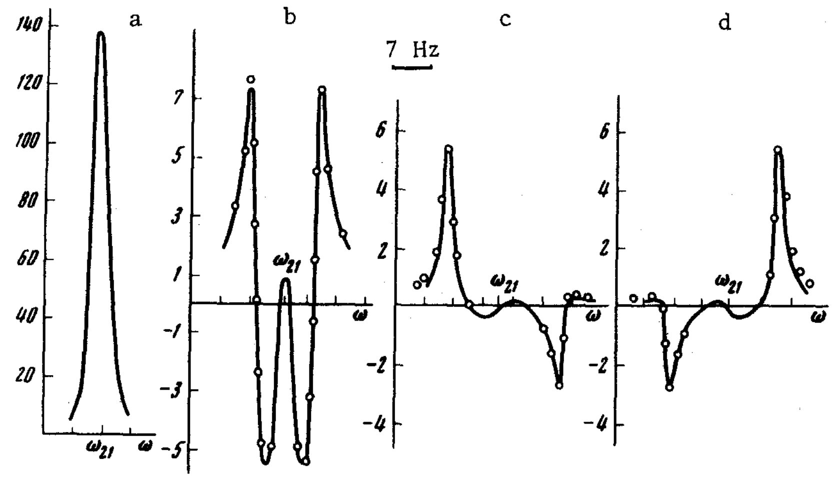

Fig. 2. Plot of the imaginary part of the susceptibility $\chi''(\omega)$: a) $H_0 = 0$; b) $\omega_0 = \omega_{21}$, $V_0 = 2\gamma$; c) $\mathcal{E}_0 = \omega_{21} - \omega_0 = -2\gamma$, $V_0 = 5\gamma$, d) $\mathcal{E}_0 = 2\gamma$, $V_0 = 5\gamma$. The solid lines are experimental in Fig. 2a and theoretical in Figs. b, c, and d. The crosses in Figs. b, c, and d are experimental.

The theory of the change of the absorption line shape and of the dispersion of a two-level system in an intense radiation field was developed by Rautian and Sobel'man in (1961). They were the first to predict the change in the refractive index without population inversion [4]. The susceptibility of a two-level system in a form most convenient for comparison with our experiment was obtained in [5] and is given by

$$\chi'(\omega) = -\frac{|\mu|^2}{\hbar} q_{st} \,\mathrm{Im}\left\{\frac{(\gamma - i\mathcal{E})(\gamma - i\mathcal{E}_0)(\gamma - i\mathcal{E}_0 - i\mathcal{E}) + 2i\mathcal{E}|V_0|^2}{(\gamma - i\mathcal{E}_0)L(-i\mathcal{E})}\right\},$$

$$\chi''(\omega) = \frac{|\mu|^2}{\hbar} q_{st} \,\mathrm{Re}\left\{\frac{(\gamma - i\mathcal{E})(\gamma - i\mathcal{E}_0)(\gamma - i\mathcal{E}_0 - i\mathcal{E}) + 2i\mathcal{E}|V_0|^2}{(\gamma - i\mathcal{E}_0)L(-i\mathcal{E})}\right\},$$

$$q_{st} = \frac{q_0}{1 + 4|V_0|^2(\mathcal{E}_0^2 + \gamma^2)^{-1}},$$

$$L(x) = x^3 + 3\gamma x^2 + (\mathcal{E}_0^2 + 3\gamma^2 + 4|V_0|^2)x + \gamma(\mathcal{E}_0^2 + \gamma^2) + 4\gamma|V_0|^2.$$

Here $\chi'(\omega)$ and $\chi''(\omega)$ are the real and the imaginary parts of the susceptibility $\chi(\omega) = \chi'(\omega) + i\chi''(\omega)$, $q = \rho_{11} - \rho_{22}$ is the difference between the populations of the lower and upper level, q_0 is the initial population difference, $V_0 = i\vec{\mu}\cdot\vec{H}_0/2\hbar$ is the matrix element of the interaction of the system with the field $\vec{H}_0$, and $\mathcal{E} = \omega - \omega_0$. The plots of the susceptibility calculated from these formulas are shown in Figs. 2 and 3 and agree with the measured values within the limits of the measurement accuracy.

It seems to us that the possibility of obtaining gain without population inversion can be a new interesting method of developing stimulated-emission amplifiers and generators. In the optical bands, the most promising for this purpose are apparently atomic vapors with narrow absorption line and large oscillator strengths. Thus, in saturated alkali-metal vapors the

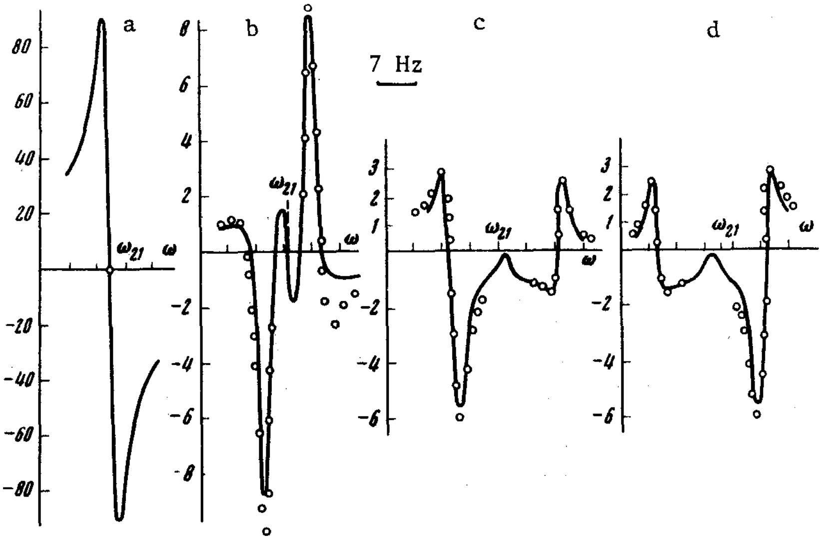

Fig. 3. Plot of real part of the susceptibility $\chi'(\omega)$ at the same parameters as in Fig. 2.

principal absorption doublets have an oscillator strength ~ 1, and the maximum attainable absorption coefficients are of the order of 10^4 cm^{-1} at a line width 0.03 cm^{-1}. Estimates show that when lasers of intensity on the order of 10^8 W/cm^2 is used, it is possible to obtain gains on the order of 10^2 cm^{-1} in a tuning range on the order of 100 Å relative to the atomic lines, at a gain line width on the order of 10^{-2} Å. An important question in connection with such amplifier, not investigated before, is the monochromaticity required of the exciting radiation. Experiments in this direction are now in the planning stage.

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INVESTIGATION OF IMPURITY DIFFUSION IN A TOKAMAK BY SPECIAL METHODS

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By comparing the experimental and calculated carbon impurity ion intensity lines in a Tokamak hydrogen plasma we show that the ions diffuse towards the pinch axis. We estimate the densities of the impurity-ion diffusion flux and the contribution of the impurities to the proton diffusion flux.

We measured the distributions of the absolute intensities I(r, t) of the lines of the ions C III, C IV, and C V of the carbon impurities and of the lines of hydrogen atoms over the cross section of the plasma filament in the TM-3 installation operating with an electron density $n_e \sim 5 \times 10^{12}$ cm^{-3} and a temperature $T_e \sim 300 - 400$ eV. At the indicated rather low electron densities, the line emission intensity is directly proportional to the concentration of the emitting ion n_k (k = 0, 1, ... z is the ionization multiplicity and z is the charge of the nucleus), and is governed together with the concentration, as follows directly from the equation for the conservation of the number of ions of a given kind [1]

$$\frac{\partial n_k(r,t)}{\partial t} = -\operatorname{div} j_k(r,t) + f_k(n_e, T_e, r, t) \qquad (1)$$

by three processes: a) the rate of population of the given ionization multiplicity f_k (ionization, recombination, etc.; the concrete form of f_k depends on the choice of the model of the population processes); b) by the diffusion of the impurity ions (div $\vec{j}_k$, where $\vec{j}_k$ is the density of the diffusion flux of the ion k), c) the entry of the impurity into the plasma from the periphery in the course of the discharge (it determines the boundary conditions, which will not be written out here).