Investigation of the spectrum of the refractive index of potassium atoms in a resonant optical field

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The method of interference spectroscopy was used in an experimental study of the behavior of the dispersion of the refractive index of potassium atoms near the D lines of the main doublet in a strong quasiresonant ruby laser radiation field and the weak probe radiation from a dye laser emitting as a result of transitions adjoining those in the ruby laser. A quantitative comparison of the theoretical and experimental results showed that they agreed well. A study was made of the spectra concentration of the radiation in the dye laser containing atomic potassium vapor inside the resonator when an adjacent transition was subject to a strong radiation field from the ruby laser.

1. INTRODUCTION

Shifts and splitting of the D lines of the main doublet of potassium atoms were observed[1,2] in a strong optical radiation field of a ruby laser. An investigation of the absorption spectrum of potassium atoms reported in Ref. 3 was carried out by photographic recording of weak probe dye laser radiation. The experimental technique used in Ref. 3 was unsuitable for a quantitative comparison between theory and experiment.

2. THEORY

The fullest and most consistent theory of a change in the susceptibility spectrum of atoms in a three-level system is given in the monograph of Apanasevich.[4] The problem simplifies greatly in the case of potassium atoms because the wavelength of the radiation emitted by a ruby laser (694.3 nm) is close to the wavelength of the $4P_{3/2}$–$6S_{1/2}$ transition ($\lambda = 693.9$ nm). If the polarization of probe radiation is parallel to the polarization of the ruby laser radiation, the theoretical model of a potassium atom for the observation of the susceptibility spectrum of each of the D lines reduces to a three-level system: level 1 is $4S_{\pm 1/2}$, level 2 is $4P_{\pm 1/2}$, and level 3 is $6S_{\pm 1/2}$.

The dispersion of the refractive index in the presence of a strong field of frequency ω_2 and a weak probe field of frequency ω is described by the following expression which applied at the weak field frequency[4]:

$$n-1 \sim \mathrm{Im}\left[\frac{\{\gamma_{31}+i[\Delta_2+(\omega_{21}-\omega)]\}N+|V_{23}|^2M/(\gamma_{32}+i\Delta_2)}{\{\gamma_{31}+i[\Delta_2+(\omega_{21}-\omega)]\}[\gamma_{21}+(\omega_{21}-\omega)]+|V_{23}|^2}\right], \qquad (1)$$

where $\omega_2 = \omega_{32} - \omega_2$ is the mismatch between the frequency of the strong field and the frequency of the transition between the levels 2 and 3; $|V_{23}|^2 = (d_{23}E/\hbar^2)$; d_{23} is the matrix element of the transition; E is the intensity of the strong field; ω_{21} is the frequency of the transition between the levels 2 and 1, probed by the weak field of frequency ω; γ_{31}, γ_{21}, and γ_{32} are the widths of the corresponding transitions; N and M are the normalized differences between the populations of the levels 1 and 2 and 2 and 3, respectively, modified by the action of the strong field on the 2–3 transition. It is assumed that the weak field does not alter the difference between the populations of the levels 1 and 2.

In our experiments we used a quasiresonant strong ruby laser radiation field satisfying the conditions $\gamma_{31}^* \ll \gamma_{21}$ and $|V_{23}|^2 \ll \Delta_2^2 - \gamma_{21}^2$, where $\gamma_{31}^* = \gamma_{31} + \delta\omega$ and $2\delta\omega$ is the width of the emission spectrum. The absorption line due to the 1–2 transition then splits into two components: a one-photon component of frequency $\omega = \omega_{21} - \Delta_1$ and a two-photon component of frequency $\omega = \omega_{21} + \Delta_2 + \Delta_1$ (for reasons behind this interpretation see Refs. 3 and 5), where

$$\Delta_1 = \frac{1}{4}\,\frac{\omega_{32}-\omega_2}{(\omega_{32}-\omega_2)^2+\gamma_{21}^2}\,\frac{d_{32}^2E_2^2}{\hbar^2} \qquad (2)$$

(ω_{21} is the frequency of the 1–2 transition).

3. EXPERIMENTAL METHOD

The most precise method for investigating the dispersion of the refractive index of an atomic medium is based on interference. In this method an interferometer is "crossed" with a spectrograph and interference fringes in the exit plane of the spectrograph represent, on some scale, the dispersion curve near the absorption lines of the atomic medium.

In our case the source of a probe field was a dye laser pumped by radiation from a ruby laser transmitted by an atomic vapor of potassium. We used the experimental setup shown in Fig. 1. Radiation from a ruby laser 1 with a KS-19 glass passive Q switch (pulse duration $\sim 3\times 10^{-8}$ sec, energy per pulse ~ 1 J) was coupled out via a resonance reflector (representing a pile of two glass plates). The ruby laser radiation interacted with a vapor of potassium atoms, which were formed as a result of evaporation and dissociation of potassium salts in an arc discharge (the current was ~ 4 A). The support of the arc discharge 2 was placed in one of the arms of a four-plate Mach-Zehnder interferometer. The ruby laser radiation transmitted by the atomic potassium vapor was directed by a rotatable prism 3 to a cell 4 containing a dye. The dye cell 4 was made of quartz and had windows oriented at the Brewster angle, which ensured linear

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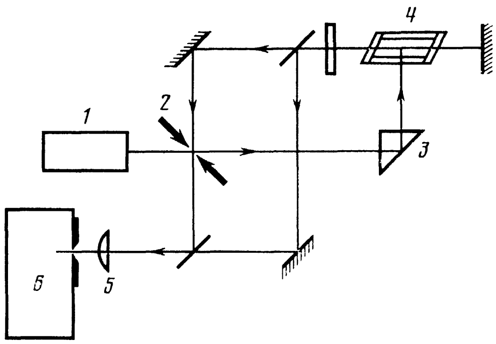

FIG. 1. Schematic diagram of the apparatus: 1) ruby laser; 2) arc discharge; 3) prism; 4) dye cell; 5) cylindrical lens; 6) spectrograph.

polarization of the probe field. The dye laser radiation beam was expanded by a telescope, which ensured that the weak-field approximation was satisfied (see Sec. 2) and was directed to the interferometer. The width of the emission spectrum of the dye laser was ~ 10 nm and it was centered in the region of ~ 767 nm. Part of the dye laser radiation transmitted by the atomic potassium vapor was combined with the radiation traveling in the other arm of the interferometer and, after focusing by a cylindrical lens 5, reached the entry slit of a spectrograph 6 (inverse linear dispersion ~ 0.5 nm/mm). The interferometer was adjusted so that between four and six interference fringes oriented parallel to the dispersion direction of the spectrograph appeared in its exit plane. Interference patterns were recorded on I-840 photographic plates.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows an interference pattern representing the dispersion near a resonance transition obtained under the action of the quasiresonant ruby laser radiation field representing an adjacent transition. A comparison of the experimental dependence of the refractive index on the wavelength with the theoretical dependence was made after determining the parameters occurring in Eq. (1). These parameters were as follows: $\gamma_{21} = 1.8\times 10^{11}$ sec^{-1} (deduced from the width of the emission line in the arc discharge). $|V_{23}| = 3.9\times 10^{12}$ sec^{-1} (calculated from the measured power density $I = 4.55\times 10^{7}$ W/cm^2), and tabulated value of the oscillator strength $f_{23} = 0.1$ (Refs. 7 and 8). The energy of the ruby laser pulses was ~ 14 J, the pulse duration was ~ 30 nsec, and the cross-sectional area of the laser beam was ~ 1 cm^2. The continuous curve in Fig. 3 is a theoretical curve calculated numerically using the above parameters and normalized to the maximum of the experimental dependence. We can see from Fig. 3 that, to within the limits of the experimental error (represented by vertical segments in this figure), the experimental and theoretical dependences were close to one another. The observed position of a two-photon absorption line agreed with that calculated theoretically. The quadratic Stark shift Δ_1 at the radiation power density given above could be found from the experimental results of Ref. 5, it amounted to $\Delta\lambda_{St} = 0.029$ nm, whereas computer calculations carried out using the above parameters Δ_2 and V_{23} substituted in Eq. (1) gave $\Delta\lambda_{St} = 0.031$ nm. Therefore, the experimental results were in good agreement with the theoretical predictions.

We also studied experimentally the spectral concentration of the dye laser radiation near the D absorption lines of potassium atoms when these atoms were inside the dye laser resonator.

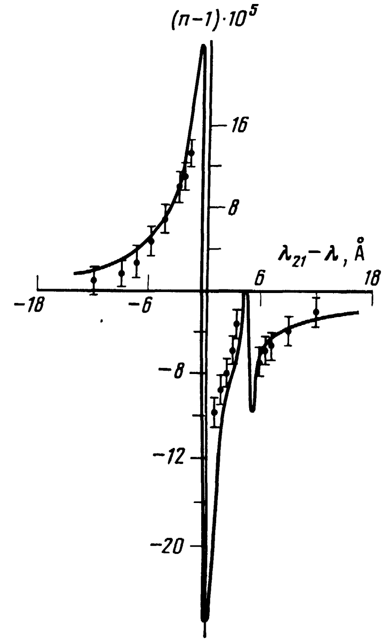

FIG. 3. Dependence of the refractive index on the wavelength (the vertical segments represent the experimental results).

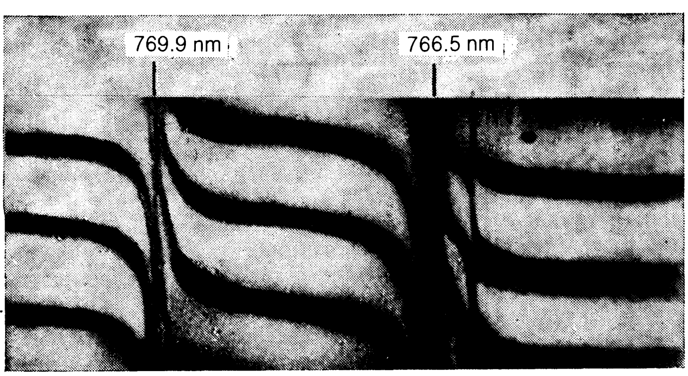

FIG. 2. Interference pattern reflecting the behavior of dispersion near a resonance transition.

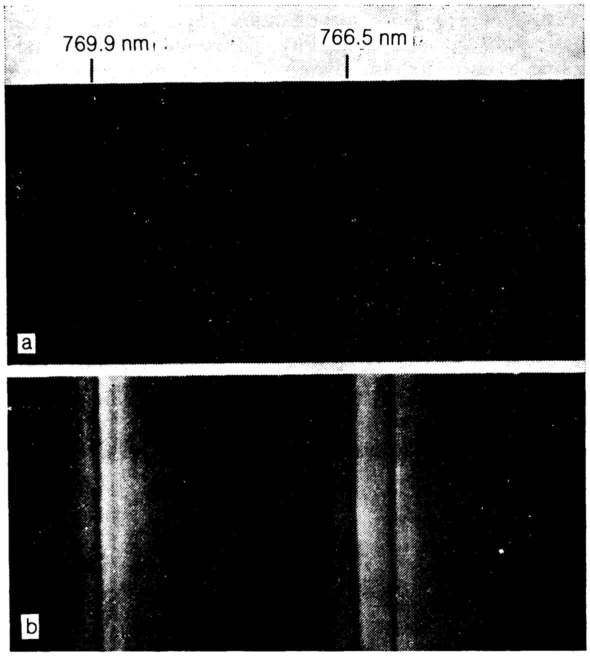

FIG. 4. Emission spectrum of a dye laser with potassium atoms inside the resonator: a) in the absence of ruby laser radiation; b) when ruby laser radiation interacts with potassium atoms.

Spectral concentration of the dye laser radiation (enhancement and weakening of the intensity in the emission spectrum) occurred when the ruby laser radiation was transmitted by the potassium vapor. When the ruby laser radiation bypassed the atomic potassium vapor, the emission spectrum of the dye laser was characterized by a uniform intensity near the weak D absorption lines (Fig. 4a). The position and the nature of the regions of enhancement and weakening of the intensity in the emission spectrum of the dye laser were in good agreement with a theoretical model proposed in Ref. 9. According to this model, the ruby laser radiation forms in an atomic medium a frequency dependent gradient of the refractive index which is responsible for frequency-dependent focusing or defocusing of the dye laser radiation. The behavior of the refractive index of an atomic medium demonstrated in Fig. 3 can be used to determine the regions of frequency-dependent focusing and defocusing $[\delta(n-1)>0$ and $\delta(n-1)<0]$ of wide-band dye laser radiation. These regions agreed well with the experimental results (Fig. 4b).

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