Feedback spectroscopy of atomic resonances

V. I. Yudin,[1,2,3,4,*] A. V. Taichenachev,[1,2,4] D. I. Sevostianov,[5,6] V. L. Velichansky,[4,5,6]
V. V. Vasiliev,[6] A. A. Zibrov,[4,7] A. S. Zibrov,[2,6,8] and S. A. Zibrov[4,6,†]
[1]*Institute of Laser Physics, Siberian Branch of RAS, Novosibirsk 630090, Russia*
[2]*Novosibirsk State University, Novosibirsk 630090, Russia*
[3]*Novosibirsk State Technical University, Novosibirsk 630092, Russia*
[4]*Russian Quantum Center, Skolkovo, Moscow Region 143025, Russia*
[5]*National Research Nuclear University (MEPhI), Moscow 115409, Russia*
[6]*Lebedev Physical Institute, RAS, Moscow 117924, Russia*
[7]*Center for Astrophysics, Harvard University, Cambridge, Massachusetts 02138, USA*
[8]*Physics Department, Harvard University, Cambridge, Massachusetts 02138, USA*
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We propose a general alternative spectroscopic approach that uses a feedback control of the input probe field parameters to stabilize the medium's response at a fixed constant level while taking the spectra. In this case the extractable spectroscopic information is contained in the variable input parameters. Along this line, we have found a universal and simple way, using the spontaneous emission for feedback control, to dramatically increase the amplitude, contrast, and quality factor of different atomic resonances. Our method, unlike the conventional spectroscopy, does not require an optically dense medium. Theoretical analysis has been experimentally confirmed with spectroscopy of the dark resonance in atomic rubidium vapor. The considerable increase (2 orders) of the resonance amplitude and a threefold decrease of the width have been observed in optically thin medium. As a result, the quality factor of the dark resonance is increased by 2 orders of magnitude and its contrast reaches a record level of 260%. Different schemes, including magneto-optical Hanle spectroscopy and Doppler-free spectroscopy, have also shown an enhanced performance by using the proposed technique.

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Over time the conventional spectroscopy has established a certain requirement to take a medium's response as a function of frequency of the probing field while the rest of the input parameters (intensity, polarization, spatial distribution, etc.) are kept at a constant level. Instead, we suggest to fix a certain medium's response to a constant level (during the frequency scanning) by manipulation of the input probing field via feedback control. In this case the changes of the governed input parameters imitate the medium's spectrum. To test our concept we have applied it to a well-known phenomenon-coherent population trapping (CPT) [1–4].

The main feature of CPT consists of the existence of the so-called dark state $|\mathrm{dark}\rangle$, which is a coherent superposition state and nullifies an atomic-light interaction operator $\hat{V}$: $\hat{V}|\mathrm{dark}\rangle = 0$. In the dark state the atoms neither absorb nor emit a light. For the modern laser metrology the importance of CPT lies in the development of miniature (including chip-scale) atomic clocks [5–7] and magnetometers [8–11]. These devices are based on a two-photon resonance formed in a bichromatic laser field, in which the frequency difference of the spectral components $(\omega_1 - \omega_2)$ is varied near the hyperfine splitting Δ. For such spectroscopy the existence of a pure coherent state $|\mathrm{dark}\rangle$, which is sensitive to the two-photon detuning $\delta_R = (\omega_1 - \omega_2 - \Delta)$, leads to a significant increase of the contrast and quality factor (amplitude-to-width ratio) of the CPT resonance in combination with a decrease of its light shift. Namely, it explains why for alkali-metal atoms the D_1 line is much preferable in comparison with the D_2 line, for which the pure dark state is absent in the cases of Doppler and/or collisional broadening of the optical line [12,13]. Pursuing a higher resonance contrast, the new polarization schemes have been implemented [13–19] for systems not possessing a trapped Zeeman state, which is insensitive to the two-photon detuning. The Ramsey effect narrows the CPT resonance and gives some increase of its quality [16,20–23].

However, to date, within the bounds of traditional spectroscopy the ways to improve the CPT resonances seem to be exhausted. A further improvement of the quality factor can be achieved by increasing the number of atoms interacting with light, but it contradicts the goals of minimization of the size and power consumption of the CPT-based atomic clocks and magnetometers. Moreover, although the high atomic density gives some increase of the resonance contrast, in an optically thick medium the nonlinear effects distort the resonance line shape [24] and, consequently, reduce the metrological characteristics of the resonance.

As we mentioned above, in this paper we propose an alternative spectroscopic technique, which was tested in detail for the CPT resonance. In particular, while conventional spectroscopy records the spectra at fixed light intensity, we use an electronic feedback control *to change* the input intensity in a way such that the level of the spontaneous fluorescence is constant during the frequency scanning. This results in a radical increase of the CPT resonance contrast together with narrowing of its width. Our method does not require a high optical density and is quite effective in small atomic cells or at lower temperatures, thus opening new opportunities for laser spectroscopy and metrology.

*viyudin@mail.ru
†serezha.zibrov@gmail.com

To explain the basic idea of our method let us consider the general case, when an atomic medium is illuminated by the light with frequencies $\{\omega_j\}$. Each component ω_j has a number of different input parameters (power, polarization, phase, spatial distribution, etc.) to which we assign the unified symbol Q_j. All possible responses of the medium can be formally represented as the functions $S_a(\omega_1,\ldots,\omega_j,\ldots;Q_1,\ldots,Q_j,\ldots)$, where the index a labels the type of the medium's response (such as absorption, spontaneous emission, output intensity and phase, polarization, refraction index, and so on). In these terms, the *conventional spectroscopy* studies the frequency dependencies $S_a(\omega_1,\ldots,\omega_j,\ldots;Q_1,\ldots,Q_j,\ldots)$ at a set of constant input parameters $\{Q_j\}=\text{const}$.

In contrast, we propose another scenario, when at least one of the medium's responses, S_b, is fixed at a constant level (during frequency scanning) by applying feedback to the manipulated input parameters Q_j:

$$S_b(\omega_1,\ldots,\omega_j,\ldots;Q_1,\ldots,Q_j,\ldots)=\text{const},\qquad \{Q_j\}\neq\text{const}. \tag{1}$$

In this case, Eq. (1) defines the frequency dependencies of the input parameters $Q_j(\omega_1,\ldots,\omega_j,\ldots)$, which imitate a medium's spectrum. This approach we name the *feedback spectroscopy*. Besides $Q_j(\omega_1,\ldots,\omega_j,\ldots)$, we can also detect the frequency dependencies of other medium's responses, $S_{a'}$, where $a'\neq b$ in Eq. (1).

Note that the feedback technique per se is not new in the laser spectroscopy and metrology. For a long time the various feedback schemes have been used mostly to suppress the noises and fluctuations of the reference spectroscopic signal (for example, see [25]). In contrast, in our approach the feedback plays a key role in creating the *new spectral features* of a joint "medium + field" system in compliance with Eq. (1), which symbolizes an alternative spectroscopic conception. Along this line, we have found a universal and simple way, using the spontaneous emission for feedback control, to dramatically increase the amplitude, contrast, and quality factor of different atomic resonances.

Let us apply our method to the dark resonance, which is formed by the bichromatic traveling wave with close frequencies $\omega_1\simeq\omega_2$:

$$E(t)=f(x,y)(E_1e^{-i\omega_1t}+E_2e^{-i\omega_2t})e^{ikz}+\text{c.c.},$$

where E_j is the amplitude of the jth component ($j=1$ and 2), k is the wave number, and the function $f(x,y)$ describes the transverse field distribution in the light beam (steplike, Gaussian, and so on).

Using the density matrix formalism we consider the standard three-level Λ scheme [see Fig. 1(a)] with two optical transitions $|1\rangle\leftrightarrow|3\rangle$ and $|2\rangle\leftrightarrow|3\rangle$, which are resonant to ω_1 and ω_2, respectively. The Rabi frequencies are defined as $\Omega_1=d_{31}E_1$ and $\Omega_2=d_{32}E_2$, where $d_{31}=\langle3|\hat{d}|1\rangle$ and $d_{32}=\langle3|\hat{d}|2\rangle$ are the matrix elements of the dipole moment operator $\hat{d}$. As is well known, in such a Λ system near the energy splitting $(\omega_1-\omega_2)\approx\Delta$ a narrow two-photon dark resonance is observed.

For simplicity, we study an optically thin medium with longitudinal size L and neglect the Doppler effect. This corresponds to the case when the buffer gas collision broadening

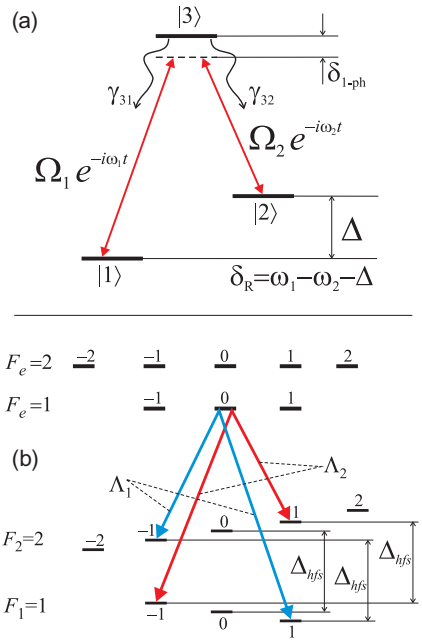

FIG. 1. (Color online) Schemes of the two-photon dark resonance: (a) a simplified three-level Λ system; and (b) two Λ systems at the D_1 line of ^{87}Rb for the Lin||Lin field configuration, which was used in experiment. Here we do not show Zeeman shifts for upper hyperfine levels with $F_e=1$ and 2.

of the optical transitions $|1\rangle\leftrightarrow|3\rangle$ and $|2\rangle\leftrightarrow|3\rangle$ exceeds the Doppler broadening. Also, we consider a steplike cylindrical transverse field distribution: $f(x,y)$=1 for $\sqrt{x^2+y^2}\leqslant r_0$ and $f(x,y)$=0 for $\sqrt{x^2+y^2}>r_0$. The typical conditions for the two-photon spectroscopy of alkali-metal atoms in the buffer gas are $\Gamma_{\text{opt}}\gg\gamma_{\text{sp}}\gg\Gamma_0$, where Γ_{opt} is the broadening of the optical transition, $\gamma_{\text{sp}}=\gamma_{31}+\gamma_{32}$ is the rate of spontaneous relaxation of the upper level $|3\rangle$ [see Fig. 1(a)] and Γ_0 is a rate of relaxation to the unperturbed equal distribution of populations at the ground states $|1\rangle$ and $|2\rangle$ (including the decay of the coherence between states $|1\rangle$ and $|2\rangle$).

Consider the scenario, when the spontaneous fluorescence S_{sp} is fixed; i.e., the total number of atoms N_e in the upper state $|3\rangle$ stays unchanged. For the optical resonance condition [$\delta_{1-\text{ph}}\ll\Gamma_{\text{opt}}$, see Fig. 1(a)] in the case of the equal Rabi frequencies $\Omega_1=\Omega_2=\Omega$ and branching decay rates $\gamma_{31}=\gamma_{32}=\gamma_{\text{sp}}/2$ it can be written as

$$\begin{aligned}S_{\text{sp}}\ &\propto\ N_e=\rho_{33}n_{\text{at}}\pi r_0^2L=\text{const}\\ &\Rightarrow\ \rho_{33}\approx\frac{2\widetilde{\Omega}^2\left[\widetilde{\Gamma}_{\text{opt}}\left(\widetilde{\Gamma}_0^2+\widetilde{\delta}_{\text{R}}^2\right)+2\widetilde{\Gamma}_0\widetilde{\Omega}^2\right]}{\widetilde{\Gamma}_{\text{opt}}^2\left(\widetilde{\Gamma}_0^2+\widetilde{\delta}_{\text{R}}^2\right)+2\widetilde{\Gamma}_{\text{opt}}\left(2\widetilde{\Gamma}_0+3\widetilde{\delta}_{\text{R}}^2\right)\widetilde{\Omega}^2+4\widetilde{\Omega}^4}\\ &=\alpha=\text{const},\quad 0\leqslant\alpha<1,\end{aligned} \tag{2}$$

where ρ_{33} is the one-atomic population in the exited state $|3\rangle$ and n_{at} is the spatial density of the atoms. The "tilde" ("~") implies that the variable has been normalized by γ_{sp} (i.e., $\widetilde{\Omega}\equiv\Omega/\gamma_{\text{sp}}$, etc.).

The expression (2) can be considered as an equation with respect to $\widetilde{\Omega}^2$, where the positive real root describes the frequency dependence of the squared Rabi frequency $\widetilde{\Omega}^2(\alpha,\delta_{\text{R}})$ on the two-photon detuning $\delta_{\text{R}}=(\omega_1-\omega_2-\Delta)$ for a given α. Since the value $\widetilde{\Omega}^2$ is proportional to the field intensity I, we

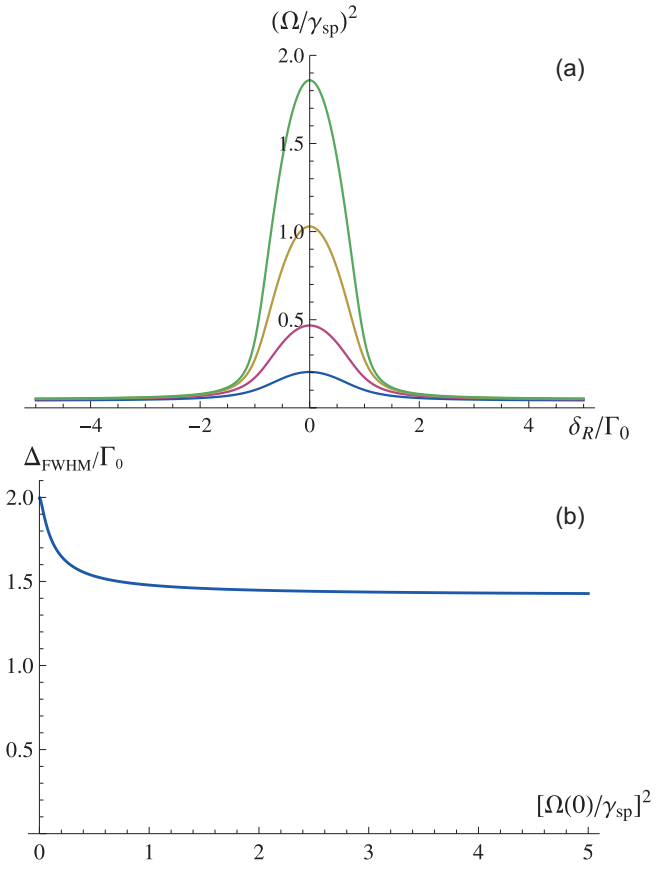

FIG. 2. (Color online) The case of $\Omega_1 = \Omega_2$. Here the following parameters have been used: $\delta_{1-ph} = 0$, $\widetilde{\Gamma}_{opt} = 100$, $\widetilde{\Gamma}_0 = 0.001$, $\gamma_{31}/\gamma_{32} = 1$, and $\alpha_{max} \approx 0.001$. (a) The calculated frequency dependence $\widetilde{\Omega}^2(\alpha,\delta_R)$ for $\alpha = 0.0008$, 0.0009, 0.00095, and 0.00097 (from the bottom to the top). (b) The normalized CPT resonance width Δ_{FWHM} as a function of the laser intensity $[\Omega(0)/\gamma_{sp}]^2$ at the two-photon resonance $\delta_R = 0$. This demonstrates the possibility of the "power narrowing" for the feedback resonance.

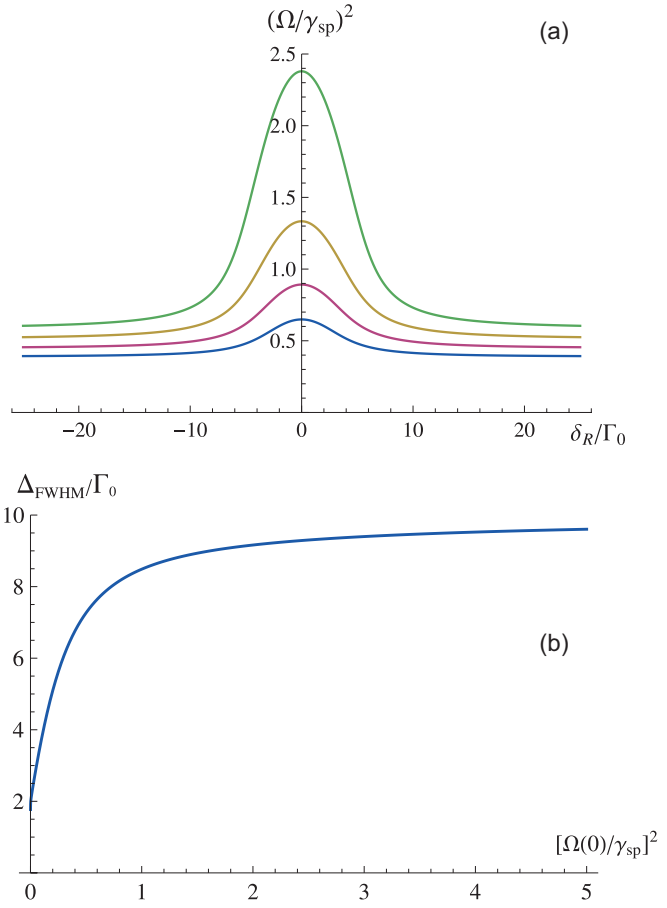

FIG. 3. (Color online) The case of $\Omega_1 \neq \Omega_2$. Here the following parameters have been used: $\delta_{1-ph} = 0$, $\widetilde{\Gamma}_{opt} = 100$, $\widetilde{\Gamma}_0 = 0.001$, $\Omega_1/\Omega_2 = 10$, $\gamma_{31}/\gamma_{32} = 3$, and $\alpha_{max} \approx 0.00195$. (a) The calculated frequency dependence $\widetilde{\Omega}_1^2(\alpha,\delta_R)$ for $\alpha = 0.0015$, 0.0016, 0.0017, and 0.0018 (from the bottom to the top). (b) The normalized CPT resonance width Δ_{FWHM} as a function of the laser intensity $[\Omega(0)/\gamma_{sp}]^2$ at the two-photon resonance $\delta_R = 0$.

obtain the frequency dependence of the input intensity $I(\alpha,\delta_R)$ for a given α.

The calculated dependencies $\widetilde{\Omega}^2(\alpha,\delta_R)$ for several values of the α parameter are presented in Fig. 2(a). As follows from the plots, the resonance amplitude significantly increases for large α parameters. At the same time, far off the resonance the dependencies remain practically unchanged. The width of the resonance is less than $2\Gamma_0$ and remains almost unaltered. It can be shown that the resonance amplitude goes asymptotically to infinity. This extreme case takes place at $\alpha \to \alpha_{max}$, where α_{max} is the limit of ρ_{33} at $\delta_R = 0$ and $\Omega^2 \to \infty$. Thus, from Eq. (2) we find $\alpha_{max} \approx \widetilde{\Gamma}_0 = \Gamma_0/\gamma_{sp}$. In general, α_{max} depends on the ratios Ω_1/Ω_2 and γ_{31}/γ_{32}, i.e., on the decay rates of the different channels [see Fig. 1(a)]. If $\alpha > \alpha_{max}$ there is an interval of δ_R (centered at $\delta_R = 0$), where the positive real root $\widetilde{\Omega}^2(\alpha,\delta_R)$ of Eq. (2) does not exist; i.e., $I(\alpha,\delta_R)$ has no physical meaning in this frequency interval. Note that the shape of the CPT resonance at $\alpha \to \alpha_{max}$ is far from a Lorentzian.

It should be pointed out that the behavior of the resonance width as a function of laser intensity is abnormal. In the case of equal intensities of the bichromatic field components $\Omega_1 = \Omega_2$ the resonance width narrows in some range of the increasing intensity [see Fig. 2(b)]. Such dependence is in contrast to the conventional spectroscopy, where the power broadening is regularly observed. Thus, the feedback spectroscopy allows one, in principle, to overcome some fundamental limitations of the traditional spectroscopy ($2\Gamma_0$ minimal width of the CPT resonances in our case). However, this "extravagant" result is not universal and for the case when $\Omega_1 \neq \Omega_2$ the calculations show some power broadening [see Fig. 3(a)]. But this broadening also has an abnormality—the saturation at large intensities [see Fig. 3(b)].

In general, the analysis made above for feedback spectroscopy of the CPT resonance clearly shows a radical increase of the contrast and quality factor, which is not related to the number of atoms (at least for optically thin medium). Indeed, the frequency dependence of the input laser intensity $I(\alpha,\delta_R)$ can be extracted from the expression for the one-atom density matrix [see Eq. (2)]. On the other hand, in conventional spectroscopy the absorption is proportional to the number of atoms. Thus, the feedback-spectroscopy method is more effective (with respect to the conventional spectroscopy) for small atomic density. We think that the number of atoms mostly

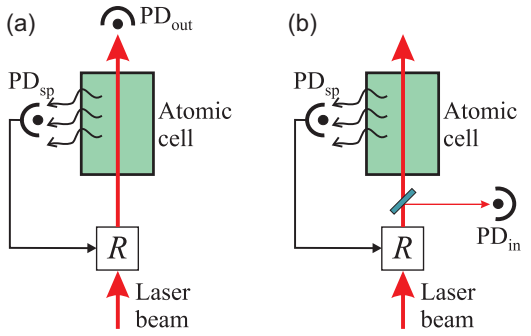

FIG. 4. (Color online) Detection of the atomic resonance in feedback spectroscopy. (a) PD_{out} photodiode detects the transmitted light S_{out}; (b) PD_{in} detects the input laser radiation S_{in}. The photodiode PD_{sp} and device R (e.g., acousto-optical modulator) form the feedback loop, sustaining the fluorescence at a fixed level.

influences the noise properties of the feedback spectroscopy, but it requires a special theoretical and experimental study.

This new spectroscopy method can be implemented in the following two ways: (a) the transmission spectrum for the optically thin medium [see Fig. 4(a)] can be described as $S_{out}(\delta_R) \propto [I(\alpha,\delta_R) - B_\alpha]$, where the constant $B_\alpha > 0$ corresponds to the constant level of the spontaneously scattered light (for given experimental conditions); and (b) the input laser intensity $S_{in}(\delta_R) \propto I(\alpha,\delta_R)$ can be detected directly before the cell [see Fig. 4(b)]. Note, in case of the laser diode employment both schemes (a) and (b) can be also implemented in other way–without external device R (e.g., by the feedback controlling of the laser current).

To verify our analysis we have used the experimental setup shown in Fig. 5. The high coherent resonant radiation of the extended cavity (ECDL) is injected into the "slave" diode laser DL, which is modulated at the frequency of the hyperfine splitting $\Delta_{hfs} = 6.8$ GHz for ^{87}Rb [see. Fig. 1(b)]. The experiment is carried out with a Pyrex cell (25 mm long and 25 mm in diameter) containing isotopically enriched ^{87}Rb and an ~5 Torr neon buffer gas. The cell is placed inside a magnetic shield. For the results reported here the cell temperature was in the range of 16 °C–41 °C.

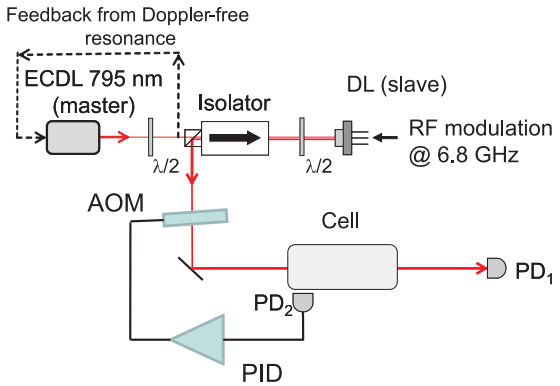

FIG. 5. (Color online) Experimental setup. The array of the photodiodes, PD_2, detects the atomic vapor fluorescence. The feedback loop (which includes the PID amplifier and the acousto-optic modulator AOM) maintains a constant level of fluorescence at its value at $\delta_R = 0$.

The laser frequency is locked to the Doppler-free saturated absorption resonance by the dichroic atomic vapor laser lock (DAVLL) technique [26]. The power of the laser radiation measured at the front window of the cell is in the 0.1–10 mW range, the beam diameter is 1–5 mm. To excite the $\Lambda_{1,2}$ schemes in the Lin||Lin configuration [see Fig. 1(b)] the carrier frequency is tuned to the $F_2 = 2 \rightarrow F_e = 1$ transition, and the high frequency side-band is tuned to the $F_1 = 1 \rightarrow F_e = 1$ transition [17].

The detector PD_2 is an array of ten photodiodes connected in parallel and equally spaced along the circumference of the the cell body. PD_2 detects 1%–5% of the fluorescence generated by the rubidium vapor. The proportional-integral-derivative controller sends the signal to the acousto-optical modulator (AOM) to lock the fluorescence intensity at the level of $\delta_R = 0$. The feedback loop has a unity gain up to ~30 kHz. The detected CPT resonances are shown in Fig. 6; the curves correspond to the ^{87}Rb transmission spectra for the two cases of "*A*" open fluorescence feedback loop and "*B*" closed fluorescence feedback loop with a lock point at the maximum of the CPT transmittance. If the feedback loop is closed at frequencies different than $\nu = \Delta_{hfs}$ the amplitude of the CPT resonance and the overall level of Doppler absorption increase (to be precise, to the level of nonresonant scattered light in the fluorescence signal). We detect an increase of the resonance amplitude and a decrease of the width (see Fig. 6). The contrast(width) of the CPT resonance without and with a feedback loop are 2%(60 kHz) (case *A*) and 260%(20 kHz) (case *B*), correspondingly. Here we use the definition of the resonance contrast I_s/I_{bg} (see Fig. 6) as in Ref. [5]. The laser power and the beam sizes for this case are 6 mW and 5×3 mm^2.

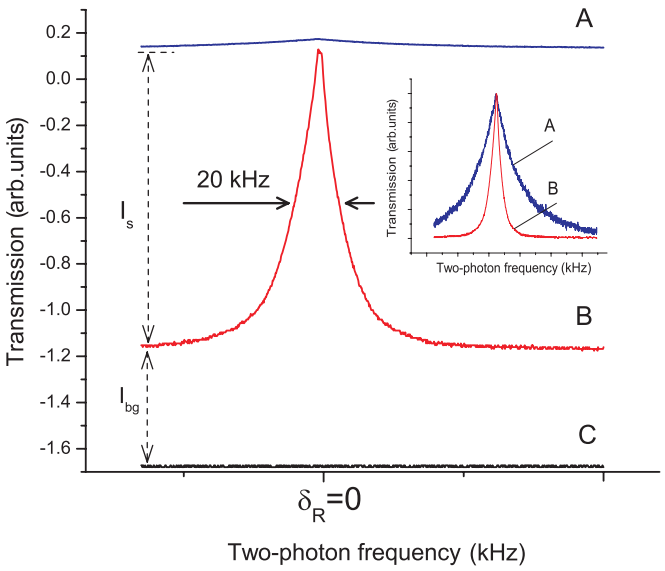

FIG. 6. (Color online) CPT transmission for unlocked *A* and locked *B* the fluorescence minimum intensity at $\delta_R = 0$ frequency. The density of the atomic vapor is 3×10^{10} cm^{-3} at 24 °C. The line *C* is the no-light level. The amplitude of the resonance in case *B* is 43 times bigger than that in case *A*. The width of the resonance decreases from 60 kHz (case *A*) to 20 kHz (case *B*). The insert is the normalized transmission of the resonance for both cases.

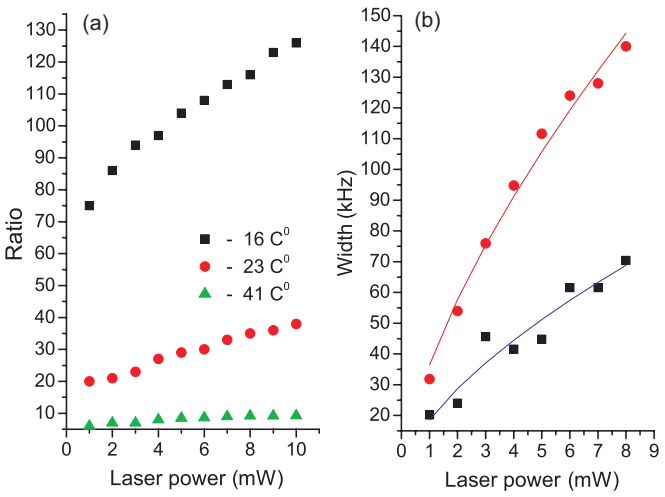

FIG. 7. (Color online) (a) The dependence of the ratio of CPT resonance amplitude for locked and unlocked fluorescence intensity on laser power at different temperatures 16 °C, 23 °C, and 41 °C. (b) The power broadening of the CPT resonance for conventional (top line) and feedback (bottom line) spectroscopy. The temperature of the atomic vapor is 23 °C; the cross section of the beam is 1.5×1.5 mm^2.

The scattered light from the window and the wall of the cell causes an additive shift of the fluorescence level. To avoid this distortion, the cell's surface is carefully cleaned. The magnitude of the scattered light is 25 times less than the maximum of the fluorescence at the CPT resonance.

In Fig. 7(a) the ratio of the EIT resonance amplitude for the cases of feedback and transmission spectroscopy are shown as a function of laser power for a set of different temperatures. One can see that the lower atomic density profits from the feedback spectroscopy method. The CPT linewidth with the feedback is 1.5–3 times less than the one achieved by means of conventional spectroscopy [see Fig. 7(b)]. The intensities in the experiment range between 30and 95 kHz or 0.36 and 4 in normalized $[\Omega(0)/\gamma_{sp}]^2$ units of Fig. 2(b). The fitting lines in the right panel have a weak nonlinearity probably due to the transversal Gaussian intensity distribution in accordance with the results of [27].

In addition to the Lin||Lin field configuration [17], the feeedback technique has been tested for other CPT schemes (Lin⊥Lin [16] and standard σ^+-σ^+ configuration), as well as for the Hanle spectroscopy of the dark magneto-optical resonance [21]. The saturation Doppler-free spectroscopy also has been tested. All of the listed schemes show the same advantages of our method.

In general, the performed experiments confirm the main results of our theoretical analysis. At low atomic vapor pressure they show a substantial increase of the resonance amplitude and a significant decrease of its width. However, instead of the "power narrowing" [Fig. 2(b)] or saturation [Fig. 3(b)] calculated at higher light intensities, our experiments demonstrate a typical power broadening, though at a slower rate compared with conventional spectroscopy methods. This contradiction with theory may come from our very simplified theoretical model. We have limited ourselves to a three-level system ignoring the rich hyperfine and Zeeman level structure of the ^{87}Rb atom [see Fig. 1(b)]. Our calculations assume that the buffer gas broadening exceeds the Doppler broadening, but this is not the case in our experiments. Moreover, these calculations were made for the steplike transversal distribution of the light intensity instead of a spatially nonuniform profile (e.g., Gaussian). Additionally, the nonresonant light scattering off the cell windows can distort the feedback loop operation.

To estimate the metrological potential of the feedback spectroscopy for atomic clocks and magnetometers, we refer to the formula for the shot noise instability limit (excepting all technical noises) of the atomic clock σ in Ref. [5]: $\sigma \propto \Gamma_r/(\sqrt{I_{bg}}C)$, where C is the contrast $C = I_s/I_{bg}$ and Γ_r is the width of the resonance. Using our experimental results it can be shown that the *estimated* clock instability σ for the feedback spectroscopy method has been decreased by 2 orders of magnitude (210 times for Fig. 6) compared to the traditional spectroscopy. This gives us real hope for a significant improvement of the stability (sensitivity) of the CPT-based atomic clocks (magnetometers). Though, additional studies of the noise are required.

The data in Fig. 7(a) confirm another result of our analysis, that the feedback spectroscopy method is more profitable (with respect to conventional spectroscopy) in less dense medium. Consequently, this gives the following advantages.

(i) The spin-exchange collision broadening will be negligibly small at room temperature, 2 orders below the effect at 75 °C, at which the existing chip-scale atomic clocks operate [5].

(ii) In hot cells the ongoing intrinsic reaction between the alkali metal and the cell body (the "curing" process) poses a serious problem for the long term frequency stability of the clock [28,29]. At lower temperatures the rate of this process is much smaller.

(iii) The Raman field parametric oscillations and other nonlinear effects are proportional to the number of atoms and are reduced by 2 orders at room temperature if compared to their impact at 75 °C [24].

Also the following fundamental issue has caught our attention—can the electronic feedback alter the physical properties of the atomic medium in our method? For example, in the 1980s it was found that the application of electronic feedback can change the essential physical property of a laser diode—its coherence [30–32]. If the feedback bandwidth is greater than the frequency spectrum of the dominating spontaneous noise, the linewidth of the diode laser is narrowed. Similarly, we could expect to have an influence of the electronic feedback on the physical properties of the medium due to the coupling between the spontaneous radiation and the laser light. In our case this coupling occurs because the fluctuations of the spontaneous emission (from all atoms) due to feedback are transferred into the laser light fluctuations and vice versa. Thus, from a general viewpoint the spontaneous field from the medium cannot be considered as a simple sum from independent atoms in free space (even for optically thin medium). In other words, under sufficiently wide-band feedback the fluctuation properties of the laser and the spontaneous fields are correlated and should be considered matched. Therefore, the suggested method needs further theoretical and experimental studies along these lines. Note that the theoretical treatment in

the present paper does not account for this correlation, which may be, in principle, an additional cause of disagreements between the experiment and the theory.

Finally, we have formulated the alternative spectroscopic conception (titled as *feedback spectroscopy*), which is symbolically expressed in the general equation (1). This approach has been theoretically and experimentally verified in detail for the CPT phenomenon, where a dramatic increase of the contrast and quality factor of the dark resonance was observed. In regard to CPT atomic clocks and magnetometers, the feedback spectroscopy might give great advantages. Moreover, different schemes (not only CPT), including magneto-optical Hanle spectroscopy as well as Doppler-free spectroscopy, also confirm the advantages of the suggested technique. Note, in our experiments we have controlled one pair of "media-laser" parameters—spontaneous radiation and input laser power. However, in the general case one can choose and manipulate any other parameters.

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