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Coherent population trapping resonances in the presence of the frequency-phase noises of an exciting field

A.V. Sokolov, A.N. Matveev, A.Yu. Samokotin, A.V. Akimov, V.N. Sorokin, N.N. Kolachevskii

***Abstract*. The influence of noises of the frequency and phase difference of an exciting bichromatic field on the parameters of coherent population trapping resonances is studied experimentally. When the phase difference fluctuates within a limited interval near its average value with a short correlation time, the resonance contrast decreases proportionally to $\exp(\phi^2_{\rm rms})$, where ϕ^2_{rms} is the phase dispersion (in rad^2). In this case, the spectral width of the resonance remains constant. In another limiting case, when the phase noise has a long correlation time, the resonance contour broadens, the area under the contour being invariable. Experiments were performed with the Zeeman sublevels of the ground state of ^{87}Rb by exciting rubidium vapour in a glass cell at the resonance wavelength of 795 nm.**

***Keywords*:** *coherent population trapping, phase noise, frequency noise.*

1. Introduction

The transformation of noises in nonlinear processes has a complicated character and depends substantially on the correlation parameters of a noise signal. Although the theoretical foundations of the transformation of stochastic signals were studied in detail more than half a century ago (see, for example, [1] and references therein), various types of noises encountered in experiments, a complexity of the mathematical apparatus, and a broad scope of nonlinear phenomena themselves require the individual analysis of one or other type of fluctuation processes.

Two-photon processes in atomic systems are widely used to excite narrow resonances, which is successfully employed in two-photon spectroscopy for applied and fundamental precision studies (see, for example, [2]). The transformation of the phase noises of electromagnetic radiation in multiphoton processes and their influence on the parameters of a two-photon resonance were investigated in experimental and theoretical papers [3 – 5]. The second harmonic generation and excitation of an atomic level by two photons with summed frequencies were considered. It was shown in these papers that the resonance shape and amplitude considerably depend on the correlation characteristics of the fluctuating phase.

Another type of two-photon processes in atomic systems is excitation of closely spaced levels of the same parity by a bichromatic field of the type $E(t) = E_1\cos(\omega_1 t + \phi_1(t)) + E_2\cos(\omega_2 t + \phi_2(t))$ via the third, highly lying level of the opposite parity. Here, E_i, ω_i and $\phi_i(t)$ $(i = 1, 2)$ are the amplitudes, frequencies, and phases of each of the field components. If the frequency difference $\omega_1 - \omega_2$ is close to the frequency of transition between the lower levels of an atomic system, the interference state of the lower levels is formed in the system, which is not coupled with the upper level by the field $E(t)$. As a result, the absorption and scattering probability for photons of this field decreases, and a narrow hole appears in the absorption (luminescence) band, which is called a coherent population trapping (CPT) resonance (see review [6]). The CPT phenomenon is widely used in optical and radiofrequency frequency standards [7 – 9], the development of highly sensitive magnetometers [10, 11], and a number of other applications. Note that the CPT resonance shape and amplitude considerably determine the limiting accuracy of measurements.

One of the cases of influence of noises of the phase and frequency difference on the CPT resonance parameters was studied theoretically in [12]. The situation was considered when the shortly correlated phases $\phi_1(t)$ and $\phi_2(t)$ of exciting laser fields fluctuated and their cross correlation was taken into account. It was assumed in [12] that the fluctuation of each of the phases and the phase difference $\phi_{12}(t) = \phi_1(t) - \phi_2(t)$ are the Wiener process [1]. This is a nonstationary process with the unlimited dispersion, which well describes the situation observed upon excitation of CPT resonances by the fields of two independent frequency-unstabilised lasers.

The phase difference $\phi_{12}(t)$ of the components of a bichromatic field is a critical parameter during the formation of a CPT resonance in an atomic ensemble [6]. To achieve the maximum amplitude and minimum width of the CPT resonance, the phase difference should remain constant. This requirement is difficult to fulfill in experiments if $|\omega_1 - \omega_2|$ exceeds 1 GHz and phase-coherent direct mod-

A.V. Sokolov P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: TeopeTuk@yandex.ru;
A.N. Matveev, A.Yu. Samokotin, A.V. Akimov, V.N. Sorokin, N.N. Kolachevskii P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; Moscow Institute of Physics and Technology (State University), Institutskii per. 9, 141700 Dolgoprudnyi, Moscow region, Russia; e-mail: art_matan@mail.ru, samokotin@dmail.com, alakimov@lebedev.ru, sovn@lebedev.ru, rjlahbox@mail.ru

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ulation methods prove to be inefficient. In this case, the exciting two-component field is produced by the methods of active stabilisation of the diffidence phase with respect to some constant phase (see, for example, [13, 14]). The stabilisation of the phase difference is achieved by using the phase-lock loop frequency control (analogue or digital) admitting a considerable dispersion of the phase difference $\phi_{\rm rms}^2$ at a constant mean value $\langle\phi_{12}\rangle$ [15, 16]. Such electronic stabilisation systems usually admit large, up to a few radians, instant deviations of the phase difference, which provides a reliable locking at long time intervals. If lasers with linewidths ~ 1 MHz are used (for example, external-cavity semiconductor lasers), the phase difference fluctuates during short time intervals $\tau_{\rm las} < (1/2\pi) \times 10^{-6}$ s, which is much shorter than the characteristic formation time of the CPT state.

Because this type of phase fluctuations is a stationary process with a certain mean value and a finite dispersion, i.e. fluctuations of the type different from that described in [12] are realised, the approach developed in [12] proves to be invalid. And since the spectral parameters of fluctuating fields considered in [12] and in the case of the active stabilisation of the phase difference are considerably different, we can expect that CPT resonances will be also substantially different. Indeed, in the first case the spectrum of the beat signal of components of the bichromatic field is described by a Lorentzian, whereas in the second case a narrow peak is observed on a broad noise pedestal [13, 14].

We proposed a model [17] describing the CPT resonance parameters (width and amplitude) depending on the dispersion $\phi_{\rm rms}^2$. It was shown theoretically that the CPT resonance width should not depend on the dispersion, whereas the resonance amplitude should decrease with increasing $\phi_{\rm rms}^2$. The contrast suppression factor χ is equal to $\exp(-\phi_{\rm rms}^2)$, where $\phi_{\rm rms}$ is expressed in radians. Note that this result coincides with conclusions made in paper [4], where excitation of a usual two-level system by quasi-monochromatic radiation with small phase fluctuations with dispersion $\phi_{\rm rms}^2$ was considered.

In this paper, we studied experimentally excitation of CPT resonances by a bichromatic field with a random phase difference $\phi_{12}(t)$ fluctuating around its mean value with short correlation times (shorter than 1 μs), the frequency difference $\omega_1 - \omega_2$ being maintained constant. As pointed out above, such a type of noise characteristics can appear in phase-lock loop frequency control systems.

We also studied another interesting limiting case of excitation of CPT resonances by a fluctuating bichromatic field with the resonance frequency $\omega_1(t) - \omega_2(t)$ fluctuating around some mean value with the correlation time above 100 μs, which greatly exceeds the CPT resonance formation time. This case is the simplest for theoretical consideration, while experimentally it can be realised, for example, by exciting CPT resonances by independent lasers emitting narrow lines of width ~ 1 kHz

2. Experiment

We studied the $5S_{1/2}(F_g = 2) \rightarrow 5P_{1/2}(F_e = 1)$ transition in a ^{87}Rb atom (F is the quantum number of the total angular momentum of the atom). The energy level diagram of this atom is presented in Fig. 1. This transition was chosen because of a large hyperfine splitting of its upper level (817 MHz) exceeding the Doppler broadening at room temperature (300 MHz), which provides optimal conditions for studying CPT resonances. When a magnetic field is applied, each of the hyperfine levels is split into $2F+1$ magnetic sublevels, and, as follows from Fig. 1b, three-level Λ-systems are formed at this transition, in which CPT states can be produced upon irradiation of rubidium atoms by σ^+ and σ^--polarised light fields at a wavelength of 795 nm.

As the magnetic field induction B is increased, the differences between the energies of the lower sublevels with $|\Delta m_F| = 2$ begin considerably differ due to nonlinearity of the Zeeman effect (m_F is the magnetic quantum number), while the splitting of the upper level with $F_e = 1$ proves to be insignificant. Thus, the frequency difference of adjacent CPT resonances for $B = 100$ G is about 3 MHz, which considerably exceeds the spectral width of the CPT resonance itself (about 0.3 MHz in this paper). The resonances themselves will be observed near the frequency difference $\Omega = \omega_1 - \omega_2 \approx 140$ MHz of the bichromatic field. Thus, by applying a magnetic field, it is possible to study isolated CPT resonances.

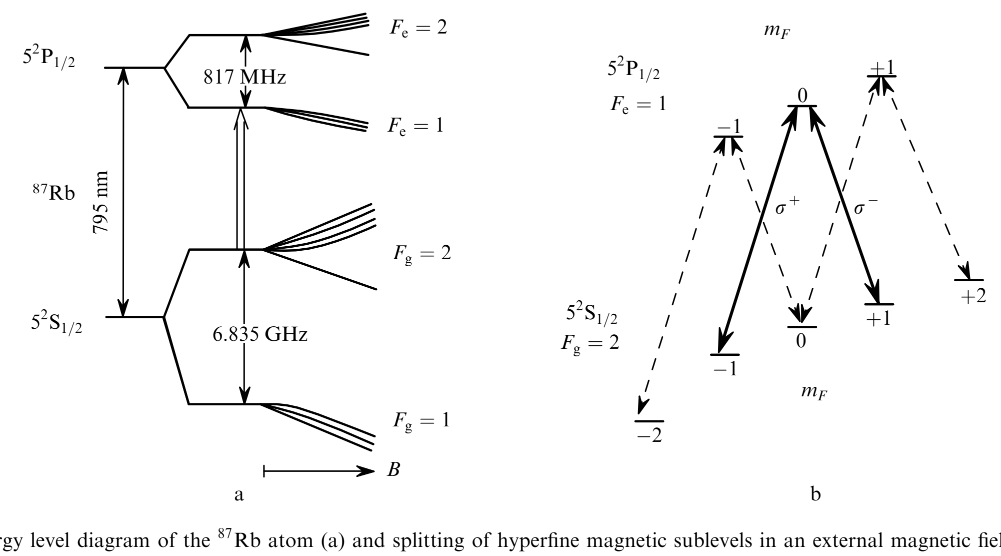

Figure 1. Energy level diagram of the ^{87}Rb atom (a) and splitting of hyperfine magnetic sublevels in an external magnetic field (b). The resonance formed on the sublevels of the ground state with $F_g = 2$ and $m_F = \pm 1$ (solid lines, b) was studied.

We studied the Λ-system with the lower levels $5S_{1/2}(F_g = 2,\ m_F = \pm 1)$. Note that rubidium atoms can undergo transitions from the upper $5P_{1/2}(F_e = 1,\ m_F = 0)$ level of this system to another $5S_{1/2}(F_g = 2,\ m_F = 0)$ sublevel of the ground state, which also removes population from the cycle of interaction with the bichromatic light field. As shown in [18], the presence of an additional decay channel of the upper level of the Λ-system does not affect the spectral width of the CPT resonance, reducing however its amplitude. In our experiments, the laser field power, laser detunings, and the density of the Rb vapour were maintained constant, which allowed us to compare the spectral parameters of resonances depending on the noise characteristics of the filed.

The CPT resonance at the magnetic sublevels of the ground state of a rubidium atom was excited and detected by using the setup shown schematically in Fig. 2. Radiation from external-cavity diode laser (*1*) in the Littrow configuration tuned to the transition wavelength of 795 nm in ^{87}Rb passed through optical isolator (*2*) and was focused to acoustooptic modulator (AOM) (*3*). The modulator operating in the first diffraction order at the frequency $\Omega \simeq 140$ MHz formed a light field at a shifted frequency, which emerged from it at a small angle. The spatial modes of light fields corresponding to the zero and first diffraction orders were combined again in a single-mode optical fibre and were additionally filtered. The power of each of the field components was about 500 μW and was kept constant. At the fibre output a pure Gaussian mode of bichromatic radiation with the beam diameter of 4.5 mm (at the 1/e level) was formed.

The light was directed into 4-cm-long cell (*4*) filled with rubidium vapour containing a small amount of a buffer krypton gas. The use of a broad beam and buffer krypton gas allowed us to reduce considerably the contribution of the time-of-flight broadening to the spectral width of the CPT resonance [19]. To provide absorption about 50% at the Doppler line maximum, the cell was heated up to 55 °C. The cell was placed inside two solenoids (*5*) – the internal one, producing a constant magnetic field with induction $B \sim 100$ G, and the external one, used for modulation. Radiation transmitted through the cell was focused on photodiode (*6*). The CPT resonances were recorded by scanning frequency Ω with the help of a PC near the CPT resonance frequency:

$$\Omega_{\text{res}} = \frac{1}{2}(g_J + 3g_I)\frac{\mu_B}{h}B \approx 1.4B\ \text{MHz},$$

where g_J and g_I are the electron and nuclear g-factors; μ_B is the Bohr magneton; h is Planck's constant; and B is induction in gauss.

A CPT signal was separated from the Doppler absorption line by the method of lock-in detection by modulating the magnetic field at frequency $f \approx 5$ kHz with generator (*7*). The output signal of a photodiode at the field modulation frequency was separated with the help of lock-in amplifier (*8*), whose readings were read out with PC (*9*). Thus, a signal proportional to the derivative of the absorption spectrum of rubidium vapour was recorded, and the recorded resonances had the dispersion shape.

To study the influence of noises on the CPT resonance shape, the phase or frequency of the output signal of high-frequency generator (*10*) feeding the AOM was modulated with the help of noise signal generator (*12*) connected to the input of the external modulation of generator (*10*). The signal of the generator may be considered as a noise signal described by the Gaussian distribution with the correlation time shorter than 1 μs. The correlation characteristics of signals were changed in some experiments (see section 4) by using low-frequency filter (*11*) with a cut-off frequency of 5 kHz. The spectrum of the beat signal of components of the exciting bichromatic field was studied by splitting a part of radiation in front of the fibre and focusing it to fast photodiode (*13*). Thus, by studying the spectrum of the beat signal with the help of spectrum analyser (*14*), we can determine mutual frequency fluctuations and phases of the field components. The spectra were recorded in the PC synchronously with CPT resonances.

Note that, aside from the noise produced by the AOM, the light fields contain phase and frequency fluctuations of the initial laser field. However, the latter remain completely

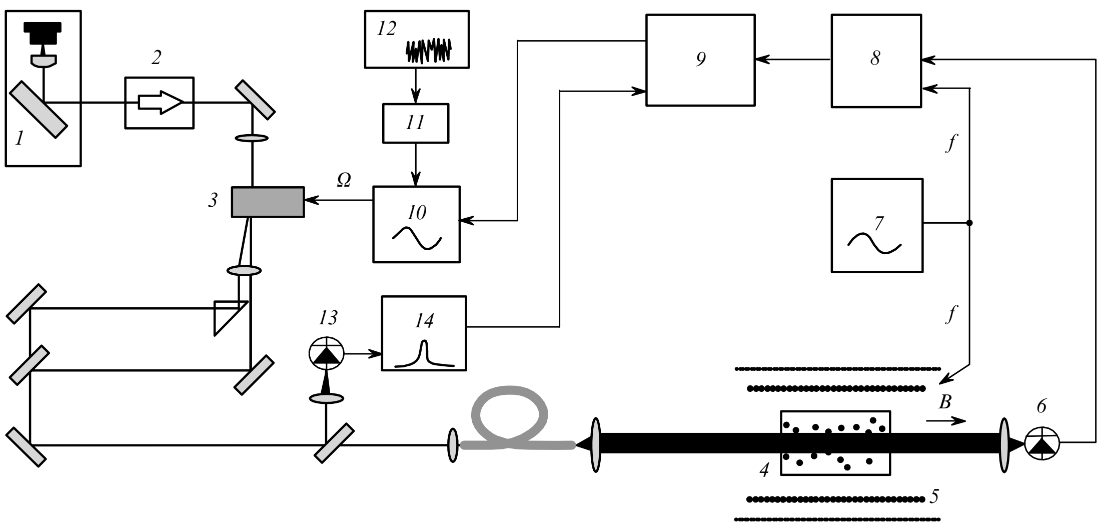

Figure 2. Scheme of the experimental setup: (*1*) external-cavity diode laser; (*2*) optical isolator; (*3*) acoustooptic modulator; (*4*) cell with rubidium vapour; (*5*) solenoids; (*6*) photodiode; (*7*) audio-frequency generator; (*8*) lock-in amplifier; (*9*) computer; (*10*) radiofrequency generator; (*11*) radiofrequency filter; (*12*) noise signal generator; (*13*) high-frequency photodiode; (*14*) spectrum analyser.

correlated in all diffraction orders of the AOM and does not affect the formation of CPT resonances [12].

3. Phase modulation

The main goal of our paper is to study CPT resonances by exciting rubidium vapour by a bichromatic field with the phase difference $\phi_{12}(t)$ fluctuating in a specific way during operation of phase-lock loop frequency control systems. We assume that the process of fluctuations of the phase difference $\phi_{12}(t)$ is stationary, with the specified mean value $\langle\phi_{12}(t)\rangle$ and dispersion $\phi^2_{\rm rms}$, and the correlation time should be much shorter than the CPT resonance formation time. This case was analysed theoretically in detail in [17], where it was shown that the noise of this type does not affect the resonance width but reduces its amplitude proportionally to $\exp(-\phi^2_{\rm rms})$.

To simulate this process, the signal of high-frequency generator (*10*) at frequency Ω was directly modulated in phase by noise signal generator (*12*) (Fig. 2), which provided the phase correlation times $\tau < 1$ μs. The AOM bandwidth allows the transfer of such noise modulation to a light field without a noticeable increase in the correlation time.

Figure 3a presents the typical spectra of a beat signal for different values of $\phi_{\rm rms}$. Each of the spectra represents a narrow peak at frequency Ω on a broad pedestal appearing due to phase fluctuations. The peak width and amplitude are determined by the resolution of the spectrum analyser. Such spectra appear when the phase modulation of a laser field is used [5, 13, 15]. It is known [4] that the ratio of the power in the narrow central peak to the total power in the spectrum for noises of this type is $\exp(-\phi^2_{\rm rms})$.

We determined the value of $\phi_{\rm rms}$ by two methods: by using the known parameters of the phase modulation of generator (*10*) and from the fraction of power in the central peak in experimental spectra. The results were completely consistent. The maximum achievable value of $\phi_{\rm rms}$ was 1.21 rad, which is determined by the modulation possibilities of generator (*10*).

Figure 3b shows the spectra of CPT signals corresponding to excitation conditions presented in Fig. 3a. As $\phi_{\rm rms}$ increases, the signal amplitude decreases, while its spectral width remains almost invariable. The spectral characteristics of CPT resonances were analysed by the resonance contrast K, which is equal to the ratio of the resonance amplitude to absorption that would be observed in the absence of CPT. Thus, for $K = 1$, the medium is completely bleached. Because the total laser power and frequency, and the cell temperature were maintained constant in our experiments, the resonance contrast proves to be proportional to the CPT signal amplitude.

According to [17], the resonance contrast should be proportional to $\chi = \exp(-\phi^2_{\rm rms})$. Figure 4a demonstrates that the expected dependence is confirmed by experimental results. The deviation of experimental data from a linear dependence at large $\phi_{\rm rms}$ (and, correspondingly, small χ) can be explained by the influence of the noise of the detecting system at small resonance amplitudes (see Fig. 3b).

Figure 4b shows the dependence of the spectral width of the CPT resonance on the phase dispersion $\phi_{\rm rms}$. One can see that the resonance width remains virtually invariable in a broad range of $\phi_{\rm rms}$, and only for $\phi_{\rm rms} \simeq 1$ rad it increases slightly, which also can be caused partially by the noise of the detecting system.

Thus, our experimental data confirm theoretical conclusions made in [17] for the case of excitation of CPT resonances in the presence of the phase difference noises representing the stationary shortly correlated Gaussian process with the dispersion $\phi^2_{\rm rms}$.

4. Frequency modulation

In experiments described in this section, we excited resonances by the field with fluctuating frequency difference, the fluctuation correlation time greatly exceeding the CPT state formation time. This case is of interest due to the simplicity of its interpretation, and it is realised in practice by stabilising the frequency of each of the exciting lasers with respect to a separate external optical cavity.

The noise signal of generator (*12*) (Fig. 2) was transmitted through low-frequency filter (*11*) with a cut-off frequency of 5 kHz and was fed to the input of the external frequency modulation of generator (*10*). The modulation depth could be varied by changing the generator signal level. Figure 5a shows typical spectra recorded with spectrum analyser (*14*). As expected, the beat signal spectrum is well approximated by a Gaussian of width $\Gamma_{\rm las}$ [1, 5]. By varying the modulation depth, we could change the value of $\Gamma_{\rm las}$ from 10 to 400 kHz. The further increase in the modulation

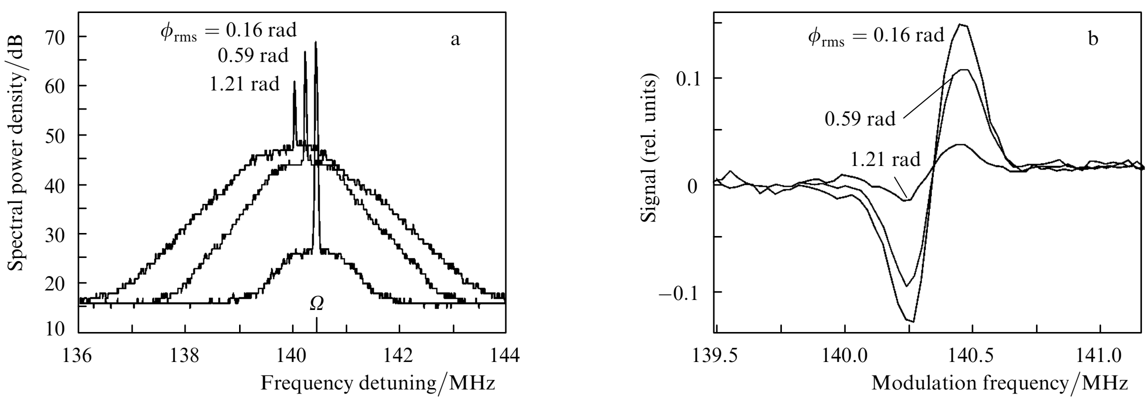

Figure 3. Spectra of the beat signal of components of a bichromatic field in the case of the phase modulation by a noise signal with short correlation times for different $\phi_{\rm rms}$. The frequency detuning is measured from the laser radiation frequency (the spectra are shifted for clearness) (a) and CPT resonances obtained by scanning the modulation frequency Ω (b).

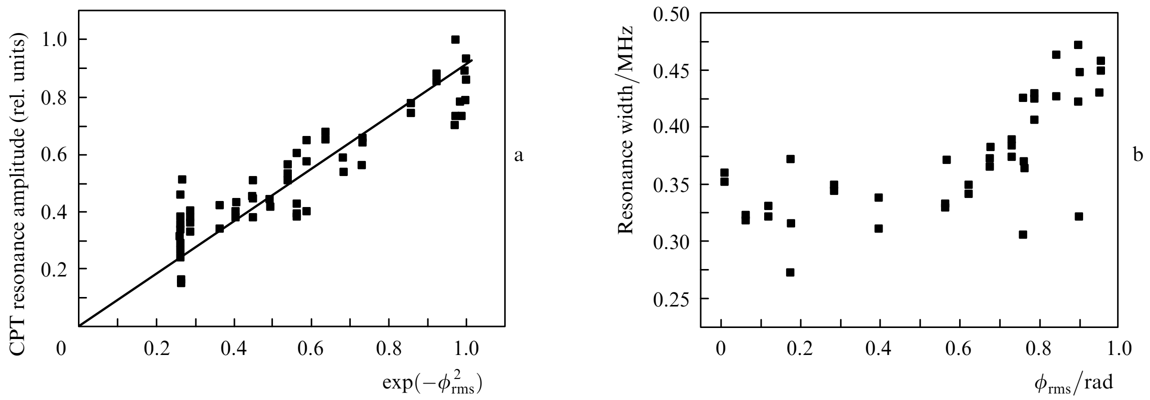

Figure 4. Dependence of the CPT resonance amplitude on $\exp(-\phi_{rms}^2)$ (dots) and its approximation by the function $a\exp(-\phi_{rms}^2)$, where a is a fitting parameter (solid straight line) (a) and the dependence of the CPT resonance width Γ_Λ on ϕ_{rms} (b).

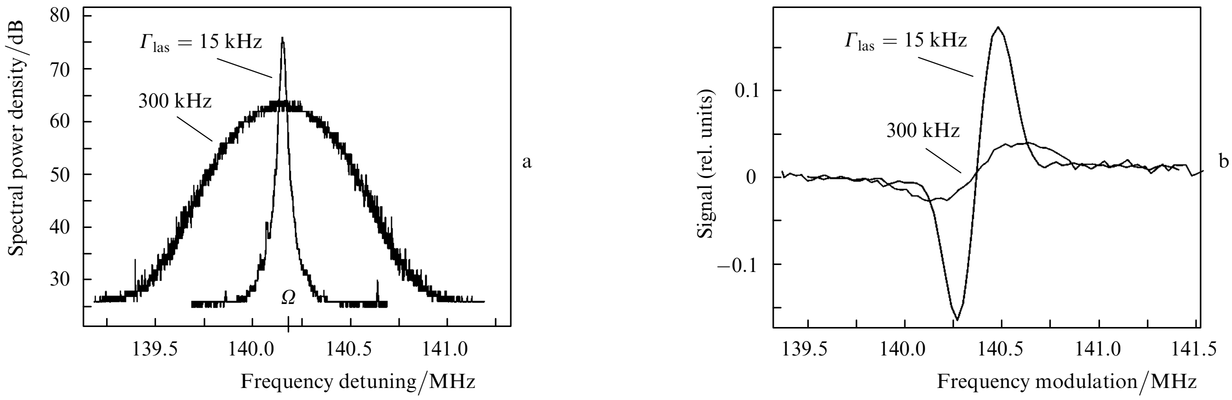

Figure 5. Spectra of the beat signal of components of a bichromatic field in the case of the phase modulation by a noise signal with large correlation times for different modulation depths and their widths (a) and CPT resonances obtained by scanning the modulation depth Ω (b).

depth was restricted by the possibilities of radiofrequency generator (*10*).

The spectra of CPT signals corresponding to the spectra of the exciting field in Fig. 5a are presented in Fig. 5b. As Γ_{las} is increased, the resonance width increases, while its amplitude decreases. Because the characteristic correlation time of the noise signal $\tau > 100$ μs considerably exceeds the characteristic CPT state formation time, which is 10 μs in our case, the atomic system has time to 'follow' the mutual phase of laser fields and to form a nonabsorbing CPT state at the corresponding instant frequency Ω. The spectral shape of the CPT resonance observed in this case should represent the convolution of the laser line with the CPT resonance, which would be observed in the absence of the frequency noise ($\Gamma_{las} = 0$).

Figure 6a presents the dependence of the CPT resonance width Γ_Λ on the beat signal width Γ_{las}. The CPT resonance width Γ_Λ was measured as the FWHM of the integrated CPT dispersion contour. The value of Γ_{las} was determined from the spectra of the beat signal recorded with the

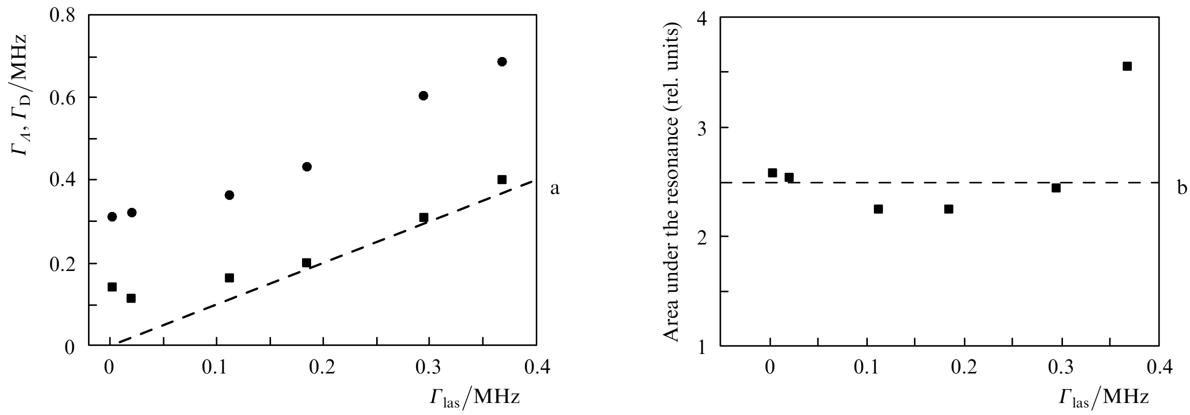

Figure 6. Dependence of the CPT resonance width Γ_Λ (circles) and the Doppler contribution Γ_D (squares) on the width of the beat signal spectrum Γ_{las}. The dashed straight lines present the dependence $\Gamma_\Lambda = \Gamma_{las}$ (a) and the dependence of the area under the CPT resonance on Γ_{las} (b).

spectrum analyser (Fig. 5a), which were approximated by a Gaussian.

For $\Gamma_{\rm las} \to 0$, the CPT resonance shape in our experiments was determined by the radiation broadening and the spatial inhomogeneity of the magnetic field and was close to a Lorentzian. This allowed us to approximate the CPT resonances by a Voigt profile and separate from it the Gaussian and Lorentzian contributions. The Lorentzian width remained virtually constant (220 ± 20 kHz) and was independent of $\Gamma_{\rm las}$. The Gaussian width $\Gamma_{\rm D}$ strongly depends on $\Gamma_{\rm las}$ (Fig. 6a). Beginning from $\Gamma_{\rm las} = 0.2$ MHz, the Gaussian contribution coincides with good accuracy with the laser linewidth ($\Gamma_{\rm D} \simeq \Gamma_{\rm las}$). This confirms the conclusion that the spectral profile of the CPT resonance is the convolution of the 'pure' CPT resonance (i.e. the resonance in the absence of phase fluctuations of the difference field, other conditions being the same) with the laser line. For $\Gamma_{\rm las} < 0.2$ MHz, the deviation from a linear dependence is observed, which can be explained by the presence of the Gaussian component in the profile of the 'pure' CPT resonance for $\Gamma_{\rm las} \to 0$ and also by approximation errors at a small Gaussian width.

Figure 6b presents the dependence of the area under the CPT resonance on $\Gamma_{\rm las}$. One can see that this area remains constant in a broad range of $\Gamma_{\rm las}$. The increase in the area at large $\Gamma_{\rm las}$ can be caused by the increase in the contribution of noises to the recorded CPT resonance at small signal amplitudes.

5. Conclusion

We have studied experimentally the spectral characteristics of CPT resonances in the presence of noises of the phase and frequency of the exciting field. Two substantially different cases have been considered: the case of shortly-correlated phase noises with a constant mean phase difference, a constant dispersion $\phi^2_{\rm rms}$, and a limited amplitude, and the case of the frequency noise with the correlation time considerably exceeding the characteristic formation time of the CPT state.

In the first case, the presence of shortly correlated phase noises in the stationary process reduces the contrast of the CPT resonance proportionally to $\exp(-\phi^2_{\rm rms})$. The width of the CPT resonance remains constant in this case in a broad range of $\phi_{\rm rms}$. This experimental observation is confirmed by theoretical conclusions that we formulated earlier in [7].

In the second case, the CPT state has time to form for each instant value of the frequency difference, resulting in fluctuations of the CPT resonance position, reproducing fluctuations of the frequency difference of the exciting field, and in the resonance broadening.

The results of this paper can be used in the study of CPT resonances with the help of laser systems in which active phase-lock loop frequency control is used. When several such independent systems are simultaneously used (see, for example, [14]), noises will be summed, which can lead to a considerable increase in the phase dispersion and a drastic decrease in the contrast of the resonance under study.

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