

# Resolution enhancement in noise spectrum by using velocity selective optical pumping in cesium vapor

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**Abstract** We demonstrate experimentally that the resolution of amplitude noise spectrum in Cs atomic vapor can be enhanced by narrowing the absorption using velocity selective optical pumping technique. It is found that the steep atomic dispersion accompanied by high absorption leads to more conversion of laser phase noise to amplitude noise, when the field propagates throughout the atoms, and meanwhile the spectral resolution is improved. The effect of optical pumping intensity on the spectrum resolution is experimentally discussed, and a theoretical explanation for this phenomenon is given, which shows that the phase-to-amplitude noise conversion is directly proportional to the dispersion of medium.

## 1 Introduction

High-resolution laser spectroscopy with atoms is a well-known experimental tool with precise measurement in

atomic physics, and it can be widely used for various applications of atomic clocks [1, 2], wavelength references [3], atomic magnetometry [4], frequency stabilization [5], slowing down [6] and storage of light [7]. In conventional high-resolution laser absorption spectroscopy, such as saturated absorption spectroscopy (SAS) [8], polarization spectroscopy (PS) [9] or velocity selective optical pumping spectroscopy (VSOPS) [10], the intensity of transmitted light throughout the samples was observed, showing the absorption variation of the samples. When the amplitude noise of transmitted laser light was observed unlike SAS, PS or VSOPS, a new type of high-resolution laser noise spectroscopy was then investigated [11], and the theoretical calculation showed that the conversion of laser phase noise to amplitude noise played a key role for this kind of intensity fluctuation spectrum, which map out the energy-level structure of atomic medium via nonlinear interaction [12]. A similar phenomenon of phase-to-amplitude noise conversion was also experimentally and theoretically discussed in different cases, such as different atomic system of Rb and Cs, high density atoms and laser linewidth dependence [13–20]. As a spectroscopic tool, it can not only be used to extract spectroscopic information on atoms [15, 17], but also for the measurement of atomic fluctuations associated to coherent (Raman) resonances between ground state Zeeman sublevels [21] and nonlinear magneto-optical effects of atoms [22].

It was demonstrated that the phase fluctuation presenting in the incident field can be transformed into amplitude fluctuation via using the absorption and dispersion properties of the atomic medium [12, 22] or using the dispersion character of a cavity [23]. One method to affect the optical-absorption and dispersion properties of atoms is using optical pumping [24]. The absorption enhancement due to velocity selective optical pumping [25] along with

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the electromagnetically induced transparency (EIT) was reported in  $\Lambda$ -type Rb atomic system [26]. Furthermore, the steep dispersion induced by velocity selective optical pumping was also demonstrated in Rb vapor, leading to a reduced or negative group velocity of light [27]. Very recently, it was shown that the EIT associated with steep normal dispersion can be enhanced via velocity selective optical pumping with multi-field pumping process in  $\Lambda$ -type Cs system [28, 29]. And the optical pumping effects on the conversion of laser-frequency modulation to intensity modulation in resonance atomic medium was also reported in a Cs vapor [30, 31], one thus expects the conversion of phase noise to amplitude noise to be affected by the optical pumping. Consequently, it appears reasonable to infer that the noise spectrum could be improved by using optical pumping effect, and the effect of optical pumping on noise spectrum was not investigated. In this paper, we first experimentally observe the enhancement of noise spectrum of the probe field with high absorption at  $D_1$  line of Cs vapor under velocity selective optical pumping, and then give a qualitative explanation for the experimental results that the enhanced conversion of laser phase noise to amplitude noise resulted from high absorption and dispersion is responsible for high-resolution noise spectroscopy.

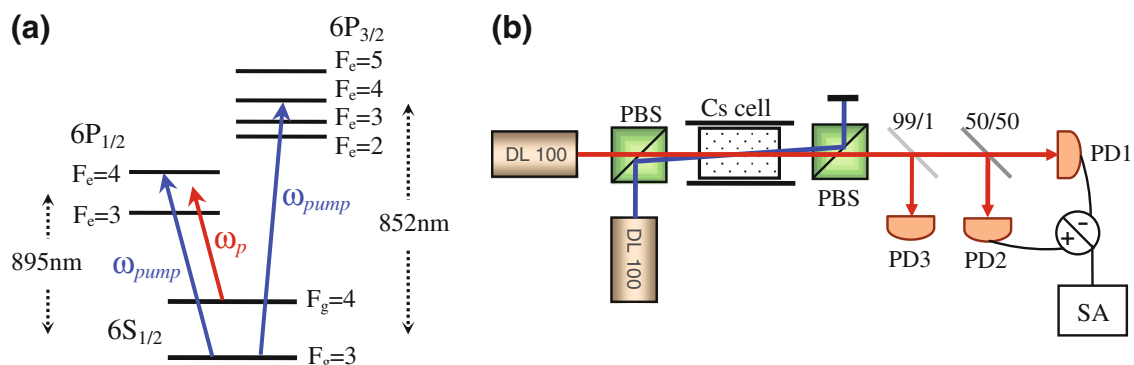
## 2 Effect of optical pumping on absorption and noise spectrum

### 2.1 Experimental setup

Figure 1a shows the relevant energy levels of  $D_1$  and  $D_2$  lines of the  $^{133}\text{Cs}$  atoms, the ground state ( $6^2S_{1/2}$ ,  $F_g = 3, 4$ ) and two excited states ( $6^2P_{1/2}$ ,  $F_e = 3, 4$  and  $6^2P_{3/2}$ ,  $F_e = 2, 3, 4, 5$ ). The spontaneous decay rates  $\Gamma$  of the upper states  $6^2P_{1/2}$  and  $6^2P_{3/2}$  are  $2\pi \times 4.6$  and

$2\pi \times 5.2$  MHz, respectively. Note that the hyperfine splitting of excited state  $6^2P_{1/2}$  is 1.168 GHz, which is larger than the Doppler linewidth at room temperature  $\Delta\nu_D \approx 405$  MHz, and the hyperfine splittings of excited state  $6^2P_{3/2}$  are 251, 201, and 151 MHz, which are all smaller than the Doppler linewidth, so the influence from additional excited levels on optical pumping effect would be introduced [28]. A weak probe field with frequency  $\omega_p$  scans across the transition  $F_g = 4 \leftrightarrow F_e = 3, 4$  ( $6^2P_{1/2}$ ), and a pump field with frequency  $\omega_{\text{pump}}$  is resonant with the transition  $F_g = 3 \leftrightarrow F_e = 4$  of  $D_2$  line or  $D_1$  line. As a result, the populations of zero velocity group atoms at the ground state  $F_g = 3$  ( $6^2S_{1/2}$ ) will be pumped to the upper state  $F_e = 4$  ( $6^2P_{3/2}$ ) or  $F_e = 4$  ( $6^2P_{1/2}$ ) by the optical pumping beam at  $D_2$  or  $D_1$  line, then these populations spontaneously decay to the ground states  $F_g = 3, 4$  ( $6^2S_{1/2}$ ). Under the condition of the pump field, the population will accumulate in  $F_g = 4$  ground level, thereby increasing the population difference of the probe transition thus enhancing the probe absorption, and correspondingly the dispersion is then enhanced. Furthermore, the noise spectrum will be changed.

Two diode lasers (Toptica DL100) with the linewidth of  $\sim 1$  MHz are employed as the probe and optical pumping sources, see Fig. 1b. The two beams with orthogonal polarizations are combined by a polarizing beam splitter (PBS), and incident upon a 7 cm-long Cs vapor cell, which is shielded against external magnetic fields by three layers of  $\mu$ -metal. The two beams are separated completely again with another PBS at the output of the cell. A small portion of the output probe field is then detected by a photodetector (PD3), which monitors the absorption spectrum, and most of the probe field is incident into a self-homodyne detection system to detect the amplitude noise. The  $e^{-2}$  full width of the probe and pump fields are 0.8 and 1.2 mm, respectively. The power of the probe field is 150  $\mu\text{W}$ , and the power of the pump field is varied from 50  $\mu\text{W}$  to 3 mW.

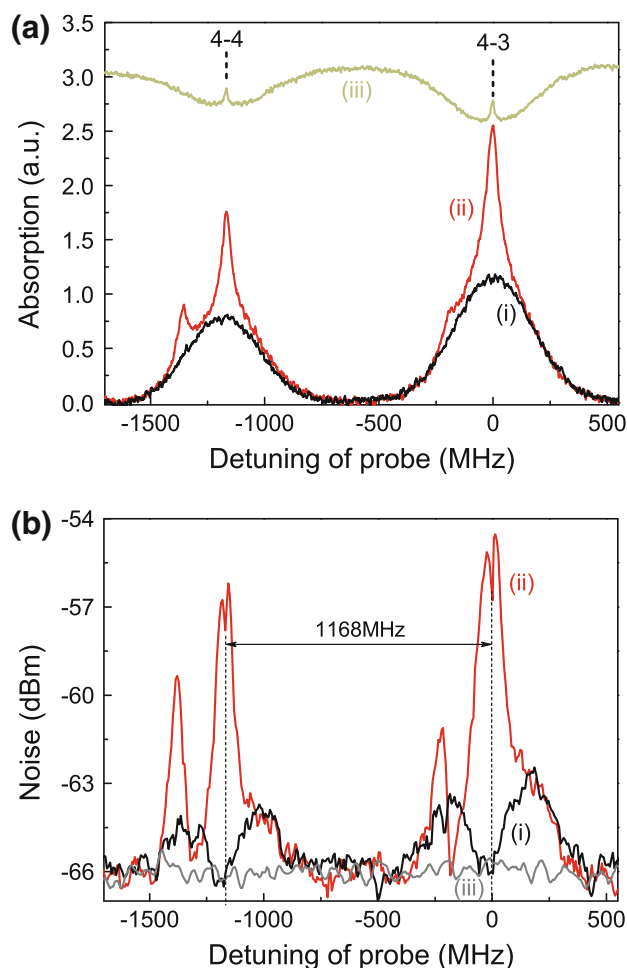


**Fig. 1** **a** Relevant energy levels of  $^{133}\text{Cs}$   $D_1$  and  $D_2$  line, **b** experimental setup. *PBS* polarizing beam splitter; *99/1*, *50/50* beam splitters; *PD1*, 2 balanced homodyne detector; *PD3* photo detector; *SA* spectrum analyzer

## 2.2 High-resolution noise spectrum of D<sub>1</sub> line with pumping at D<sub>2</sub> line

When the pump field is interacting on the transition  $F_g = 3 \leftrightarrow F_e = 4$  of D<sub>2</sub> line, and the weak probe field is scanned across the transitions  $F_g = 4 \leftrightarrow F_e = 4$  and  $F_g = 4 \leftrightarrow F_e = 3$  of D<sub>1</sub> line. The absorption and noise spectra of the probe field are observed, see Fig. 2. Compared to the normal absorption spectrum in two-level system [curve (i) in Fig. 2a], the absorption of the probe field is highly increased by using an optical pumping with the power of 0.76 mW [curve (ii)]. And the probe absorption spectrum with optical pumping shows a linewidth ( $\Delta\nu \approx 166$  MHz) smaller than that of the absorption in curve (i), i.e., the Doppler linewidth at room temperature, which is measured to be  $\Delta\nu_D \approx 405$  MHz. Curve (iii) is the relevant SAS of the probe field for D<sub>1</sub> line. Consequently in Fig. 2b, the amplitude noise spectrum of the probe field [curve (ii)] is also increased with the optical pumping, and it is much narrower than that when the pumping is switched off [curve (i) in Fig. 2b]. Curve (iii) is the shot noise limit (SNL) obtained from the difference of the photocurrent fluctuations of PD1 and PD2. We can find that the amplitude noise of curve (i), (ii) displays a typical ‘M’ shape, resulting from the phase-to-amplitude noise conversion [11, 13], just as in ordinary frequency modulation spectroscopy [32]. The height of the highest two points of the ‘M’ shape represents the phase noise of the probe light, the middle dip of ‘M’ shape corresponds to the precise transition of the atoms, and the spectral resolution is defined as the Full Width at Half Maximum (FWHM) of its response to a particular transition. By contrast, we focus on the noise power spectrum at transition of  $F_g = 4 \leftrightarrow F_e = 3$ , the noise power [curve (ii)] under optical pumping is 5.3 times (8 dB) larger than that without optical pumping [curve (i)], this enhancement of the noise spectrum is caused by the high conversion of the phase noise to amplitude noise due to high absorption of curve (ii) in Fig. 2a, resulting in the high sensitivity of the spectrum to the phase noise of probe light. And on the other hand, the dips at the middle of ‘M’ shaped curve (i) and (ii) in Fig. 2b are corresponding to the  $F_g = 4 \leftrightarrow F_e = 3$  transition resonance shown in the curve (iii) in Fig. 2a, it is obvious that resolution of the noise spectrum is improved from the 523 MHz FWHM (the width at the noise power of  $-64$  dBm, which corresponds to about the half power level of beam noise) of curve (i) to 92 MHz of curve (ii) (the width at the noise power of  $-57.2$  dBm), and correspondingly, the precision of a transition frequency measurement is improved due to the frequency resolved spectrum.

Notice that the two small peaks at the left side of the atomic resonance absorption lines and the corresponding amplitude noise signals in curves (ii) are the signals from the velocity selective optical transitions of an atomic group at an



**Fig. 2** The absorption spectrum (a) and the noise spectrum (b) of the probe field without and with the pump field versus the detuning of probe field. In (a), the curves represent (i) (black line) the absorption without the pump field, (ii) (red line) the absorption with the pump power of 0.76 mW, (iii) (yellow line) SAS for D<sub>1</sub> line. In (b), the curves are (i) (black line) the amplitude noise without the pump field, curve (ii) (red line) the amplitude noise with the pump power of 0.76 mW, curve (iii) (gray line) SNL. The spectrum analyzer is operated at the center frequency of 3 MHz with zero span; the resolution bandwidth (RBW) = 300 kHz; the video bandwidth (VBW) = 1 kHz

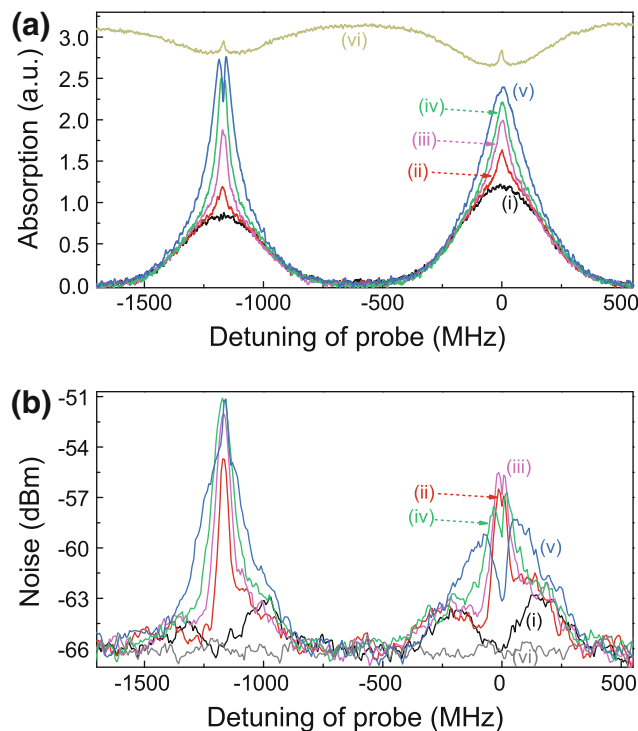
additional excited level  $F_e = 3$  of D<sub>2</sub> line, having non-zero velocity. Hence atoms of these selective velocity groups are pumped to the ground state  $F_g = 4$  of the probe absorption by the pump field, which is resonant with the transition of  $F_g = 3 \leftrightarrow F_e = 4$  at D<sub>2</sub> line, but has a detuning 201 MHz for the transition of  $F_g = 3 \leftrightarrow F_e = 3$  at D<sub>2</sub> line.

## 2.3 High-resolution noise spectrum of D<sub>1</sub> line with pumping at D<sub>1</sub> line

The comparison for optical pumping at Cs D<sub>1</sub> and D<sub>2</sub> lines is also made in the following to further show the optical pumping effect on noise spectrum. For D<sub>1</sub> line of Cs atom,

the hyperfine splitting of the excited state ( $6^2P_{1/2}$ ) is 1.168 GHz, which is larger than the Doppler linewidth, and when the optical pumping is used at the transition of  $F_g = 3 \leftrightarrow F_e = 4$  of  $D_1$  line, the nearby energy level  $F_e = 3$  would not affect the optical pumping, because the Doppler broadening is smaller than the energy-level difference.

The absorption and noise spectra of the probe field versus the detuning of the probe field for different powers of the pump field are shown in Fig. 3. As it is obtained for  $D_2$  pumping, the enhanced absorption and noise spectrum are obtained with optical pumping. As we expect, the Doppler broadening effect for off-resonant pumping for non-zero velocity atoms disappears. Furthermore, we can see that the absorption increases with increasing the power of the pump field from 0 to 3 mW. However, the corresponding amplitude noise of the output probe field, as shown in Fig. 3b gives a complex result that the output amplitude noise increases and becomes large and narrow with the weak optical pumping, and when the power of the pump field is further increased [curve (iv–v)], it will decrease for the saturation effect of pumping.



**Fig. 3** The absorption (a) and amplitude noise spectra (b) of the probe field versus the detuning of probe field for different powers of the pump field. Curve (i) without the pump field (black line), curve (ii) with the pump power of 50  $\mu$ W (red line), curve (iii) 180  $\mu$ W (pink line), curve (iv) 800  $\mu$ W (green line), curve (v) 3 mW (blue line). In (a), curve (vi) SAS for  $D_1$  line (yellow line). In (b), curve (vi) SNL (gray line). Other parameters are the same as those in Fig. 2

The signals at the left side of absorption and noise are the results for EIT resonance, because the pump field is resonant with  $F_g = 3 \leftrightarrow F_e = 4$ , and the probe field is scanned across the transition  $F_g = 4 \leftrightarrow F_e = 4$ , forming a  $\Lambda$ -type EIT system, the EIT dip can be seen in curve (v). It seems that the noise spectrum for EIT has no longer an “M” type shaped curve. The complex effect is theoretically discussed in Reference [33], there may have a double “M” shape curve, which could not be observed, because of the weak EIT effect in this case.

### 3 Theoretical analysis

We present in this section a simple theoretical model to give a qualitative explanation for the enhanced noise spectrum due to high absorption and dispersion properties of the medium with the pump field, and its dependence on the power of the pump. With respect to the condition of experiment, the system is simplified as a closed four-level model. We let levels  $|a\rangle$ ,  $|b\rangle$ ,  $|c\rangle$  and  $|d\rangle$  correspond to  $^{133}\text{Cs}$  atomic levels  $6^2S_{1/2} F_g = 4$ ,  $6^2P_{1/2} F_e = 3$ ,  $6^2P_{1/2} F_e = 4$  and  $6^2S_{1/2} F_g = 3$ , respectively. The weak probe field  $\omega_p$  couples levels  $|a\rangle$  and  $|b\rangle$  and the pump field  $\omega_{\text{pump}}$  couples levels  $|c\rangle$  and  $|d\rangle$  as depicted in Fig. 1a. The Hamiltonian of the system can be written as:

$$H = H_0 + H_{\text{int}} \tag{1a}$$

with

$$H_0 = \hbar\omega_a|a\rangle\langle a| + \hbar\omega_b|b\rangle\langle b| + \hbar\omega_c|c\rangle\langle c| + \hbar\omega_d|d\rangle\langle d| \tag{1b}$$

$$H_{\text{int}} = -\hbar\Omega e^{-i\omega_p t}|b\rangle\langle a| - \hbar\Omega_{\text{pump}} e^{-i\omega_{\text{pump}} t}|c\rangle\langle d| + h.c. \tag{1c}$$

where  $\Omega$  and  $\Omega_{\text{pump}}$  are the Rabi-frequency of the probe field and the pump field, respectively, and they are all real. In Eq. 1c the usual rotating-wave approximation is used.

Using slowly varying approximations, the density matrix equations of motion of this system are as follows:

$$\begin{aligned} \dot{\rho}_{aa} &= i\Omega(\rho_{ba} - \rho_{ab}) + \frac{\Gamma}{2}(\rho_{bb} + \rho_{cc}) - \gamma_0(\rho_{aa} - \rho_{dd}) \\ \dot{\rho}_{bb} &= -i\Omega(\rho_{ba} - \rho_{ab}) - \Gamma\rho_{bb} \\ \dot{\rho}_{cc} &= -i\Omega_{\text{pump}}(\rho_{cd} - \rho_{dc}) - \Gamma\rho_{cc} \\ \dot{\rho}_{dd} &= i\Omega_{\text{pump}}(\rho_{cd} - \rho_{dc}) + \frac{\Gamma}{2}(\rho_{bb} + \rho_{cc}) + \gamma_0(\rho_{aa} - \rho_{dd}) \\ \dot{\rho}_{ba} &= -(\gamma + i\Delta_p)\rho_{ba} - i\Omega(\rho_{bb} - \rho_{aa}) \\ \dot{\rho}_{dc} &= -(\gamma - i\Delta_{\text{pump}})\rho_{dc} + i\Omega_{\text{pump}}(\rho_{cc} - \rho_{dd}) \end{aligned} \tag{2}$$

The above equations are constrained by  $\rho_{ij} = \rho_{ji}^*$  ( $i \neq j$ ,  $i, j = a, b, c, d$ ) and  $\sum_i \rho_{ii} = 1$ .  $\Delta_p = \omega_{ba} - \omega_p$  and

$\Delta_{\text{pump}} = \omega_{cd} - \omega_{\text{pump}}$  are the detunings of the probe and the pump fields from their relevant atomic transitions, respectively.  $\Gamma$  is the natural linewidth of the upper level  $|b\rangle$  or  $|c\rangle$ . We set that the off-diagonal decay rates for  $\rho_{ba}$  and  $\rho_{dc}$  are  $\gamma = \Gamma/2$ , and the dephasing rate between the ground states  $|a\rangle$  and  $|d\rangle$  is  $\gamma_0$ , which is much smaller than  $\gamma$ . Solving for the steady state of Eq. 2, we can obtain the analytical expression of  $\rho_{ba}$ , the real and imaginary parts of which ( $\text{Re}[\rho_{ba}] \propto \chi'$  and  $\text{Im}[\rho_{ba}] \propto \chi''$ ) quantify both dispersion and absorption effects of the complex susceptibility  $\chi = \chi' + i\chi''$ , respectively [34].

In this system, the influence of Doppler broadening has to be taken into account. Considering all the atoms in the vapor cell, we need to take an integration over the velocity distribution  $f(v) = \sqrt{\frac{m}{2\pi k_B T}} \exp(-\frac{mv^2}{2k_B T})$ , where  $\sqrt{\frac{2k_B T}{m}}$  is the

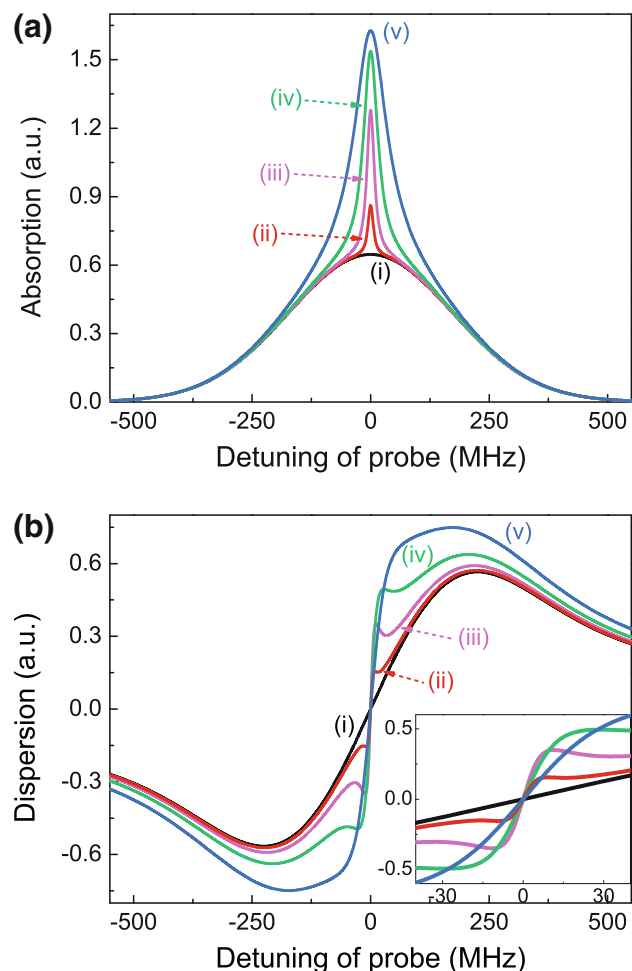
most probable speed of atoms at a given temperature  $T$ ,  $m$  is the atomic mass, and  $k_B$  is the Boltzmann constant. We make the average over all Doppler detuning by replacing the detuning  $\Delta_p \rightarrow \Delta_p + \omega_p v/c$  and  $\Delta_{\text{pump}} \rightarrow \Delta_{\text{pump}} + \omega_{\text{pump}} v/c$  for different velocities in the laboratory frame, and get the total susceptibilities [35, 36].

The total absorption and dispersion susceptibility for different Rabi-frequencies of the pump field are plotted in Fig. 4a, b. There is a good agreement between the absorption experimental results (Figs. 2a and 3a) and theory (Fig. 4a) for the absorption spectrum of probe field. Though the absorption increases with the increasing of Rabi-frequency of the pump field, the dispersion does not have the same tendency. It can be found, in Fig. 4b, that the dispersion becomes steeper in a certain range of small Rabi-frequency of the pump field, and the larger the Rabi-frequency of the pump field is, the less steeper the dispersion is [curve (iv–v)], which gives a good explanation that why the amplitude noise decreases (Fig. 3b) when the power of the pump field is further increased. So that it can be concluded that the phase-to-amplitude noise conversion is induced by the dispersion of medium, and thus leads to a high-resolution noise spectrum.

#### 4 Conclusions

We measured the amplitude noise of the transmitted field passing through a Cs vapor cell without and with optical pumping, in which atomic system, the laser phase noise can be converted to amplitude noise resulting from its dispersion; therefore, a high-resolution noise spectroscopy can be obtained. The dependence of optical pumping on the probe absorption and the corresponding noise spectrum due to phase-to-amplitude noise conversion is also discussed. We gave a qualitative explanation of this phenomenon from the perspective of atomic dispersion property. From this analysis, a high-resolution noise spectroscopy of  $D_1$  line related to the ground state  $F_g = 4$  is obtained when an appropriate power of optical pumping is employed. It is clear that the noise spectroscopy provides more hyperfine measurement for the energy-level structure and will be useful in other spectroscopic analysis. Moreover, the high-resolution noise spectroscopy can provide a useful handle to study atomic dispersion, atomic noise and light phase fluctuation. In particular, the resolution improved spectrum would be useful for phase noise detection with high sensitivity, which can not be detected directly.

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**Fig. 4** The absorption (a) and dispersion (b) spectra of the probe field versus the probe detuning for different Rabi-frequencies of the pump field. Curve (i)  $\Omega_{\text{pump}} = 0$  (black line), curve (ii)  $\Omega_{\text{pump}}/\Gamma = 0.1$  (red line), curve (iii)  $\Omega_{\text{pump}}/\Gamma = 0.3$  (pink line), curve (iv)  $\Omega_{\text{pump}}/\Gamma = 0.8$  (green line), curve (v)  $\Omega_{\text{pump}}/\Gamma = 2$  (blue line). Other parameters are  $\Gamma = 1$ ,  $\Delta_{\text{pump}} = 0$ ,  $\Omega/\Gamma = 0.1$ ,  $\gamma_0/\Gamma = 0.01$



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