Steep anomalous dispersion in coherently prepared Rb vapor

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Refractive index and dispersion were analyzed with the model recently used to study subnatural EIA resonances [12]. In this model, two monochromatic optical fields, a drive field and a weak probe field with amplitudes $E_d$, $E_p$ and frequencies $\omega_d$, $\omega_p$ respectively are incident on motionless two-level atoms with resonance frequency $\omega_0$ and electric dipole moment $\mu$. The atomic levels are degenerate. The configuration is closed. The spontaneous decay rate is $\Gamma$. Finite interaction time is described by a relaxation rate $\gamma$ ($\gamma \ll \Gamma$). The drive wave Rabi frequency is $\Omega = \mu E_d/h$ and its saturation parameter $S \equiv 2\Omega^2/\Gamma^2$.

All these investigations were carried on alkaline atoms where the absorption is strongly suppressed and dispersion is steep and normal ($D \equiv dn/d\nu > 0$) due to CPT between the two ground state hyperfine levels (A scheme). However, atomic coherence among Zeeman sublevels belonging to the same ground-state hyperfine level can led not only to usual EIT, but also to an absorption enhancement named as electromagnetically induced absorption (EIA) [10,11]. Since EIT/EIA effects in degenerate two-level systems can produce a significant variation in the absorption with subnatural width, one can predict a large absolute value of dispersion in this case. Notice that at resonance dispersion would be normal ($D > 0$) for EIT and anomalous ($D < 0$) for EIA. In both cases the absolute value of the dispersion can be several orders of magnitude greater than for a linear medium. In this letter we present the first observation of steep anomalous and normal dispersion in coherently prepared degenerate two-level atomic system.

Fig. 1. Calculated dispersion at $\delta = 0$ for the transitions $F_p = 2 \rightarrow F_s = 3$ (circles) and $F_p = 1 \rightarrow F_s = 0$ (triangles) as a function of the saturation parameter $S$. Solid(hollow) points correspond to negative(positive) dispersion. Inset: Calculated refractive index as a function of $\delta$ for linear and orthogonal pump and probe polarizations for two different transitions and same drive field intensity $[\omega_d = \omega_0, \Gamma/\gamma = 1000, \ D \lesssim 1]$. The calculated refractive index, tested by the probe wave in the presence of the drive field, as function of the frequency offset $\delta \equiv \omega_d - \omega_p$ is presented in the inset of Fig.1. The shown spectra correspond to the closed transitions in the $D_2$ line of $^{87}$Rb. The peak to peak
refractive index variation $\Delta n$ is higher for the anomalous dispersion because the transition $F_g = 2 \rightarrow F_e = 3$ is stronger than the $F_g = 1 \rightarrow F_e = 0$ transition. The corresponding absolute value of the anomalous dispersion is also larger.

The values of $D$ and $n$ depend on light intensity, atomic density $N$, level degeneracy, polarizations, among others parameters. Here we restrict our attention to the dependence with the drive-field intensity $I_d$.

Since a general expression for $n$ in driven degenerate two-level systems is not available at present, we consider as a guide the analytical expression corresponding to the ideal $\Lambda$ scheme [7]:

$$n(\delta) = 1 + \frac{3}{8\pi^2} \lambda^2 N \frac{\Omega^2 \delta}{(\Omega^2 + \Gamma/2)^2 + (\gamma/2)^2}$$  \hspace{1cm} (1)

where $\lambda$ is the wavelength of the optical transition. At low intensity ($\Omega^2 \ll \Gamma \delta$) $D$ and $n$ around $\delta = 0$ are growing linearly with $\Omega^2$. For high intensity ($\Omega^2 \gg \Gamma \delta$), $D$ and $\Delta n$ are inversely proportional to $\Omega^2$. It can be shown that the maximum for $\Delta n$ and $D$ are reached for $\Omega^2 = \Gamma/2$ when the saturation parameter $S = \gamma/\Gamma$.

Such behavior may be explained in the following way:

At low intensity, when power broadening is not significant (the width of the resonance is determined by the ground-state relaxation), the amplitude is growing linearly with intensity, while the width remains almost constant. In this case, $D$ grows linearly with $I_d$. The dispersion saturates when the resonance width is determined by power broadening. At high intensity, the refractive index and the absorption saturate [12] while the resonance width still grows. So, in this region $D$ decreases with intensity.

The calculated intensity dependences of the dispersion at resonance ($\delta = 0$) shown in Fig.1 are in qualitative agreement with the simple analytical expression (Eq.1) for low and high drive intensity. At very low drive intensity (linear absorption) the dispersion for the two transitions considered in Fig.1 is anomalous. For higher drive intensity there is absorption enhancement (EIA) for one transition and absorption reduction (EIR) for the other. The first case results in anomalous dispersion while the other corresponds to normal dispersion. The two curves have a maximum at moderate intensity ($S \lesssim 1$). At large drive intensities ($S > 10^3$) the dispersion on both transitions is normal and exhibits the same linear asymptotic behavior.

The experiment was realized on the $D_2$ line of $^{87}$Rb in a vapor cell. We used a phase heterodyne method to measure the refractive index. The idea of this approach is based on the well-known method of FM spectroscopy and the two-mode technique [13]. Our method is similar to that used for dispersion measurements [7] and for Doppler-free spectroscopy [14]. To obtain information about $n$, the phase of a RF-signal produced by mixing the resonant probe wave with a non-resonant auxiliary wave (having the same optical path) is compared to an RF reference produced by the mixing of undisturbed fractions of the probe and the auxiliary waves. The variation of the phase difference between the two RF-signals, due to the atomic medium dispersion, is $\delta \Phi = l(n - 1)\omega/c$, where $l$ is the vapor cell length. With these technique, the influence of acoustic noise is dramatically reduced compared to the homodyne method based on a Mach-Zehnder interferometer [4,6].

The scheme of the experimental setup is shown in Fig.2. A single-mode extended cavity diode laser frequency lockable to a Rb saturated absorption resonance was used. Two mutually coherent waves with tunable optical frequency offset were obtained by using two acousto-optic modulators (AOM’s 1,2) [10]. The diffracted output from AOM2, driven by a tunable RF generator, was used as the drive wave. The two outputs of AOM3 (with fixed frequency offset) were combined on the beamsplitter BS1. One of this beamsplitter outputs was used as the signal wave. It contains two frequency components, the resonant probe wave and the non resonant auxiliary wave. The second output was used to produce the RF-reference on the photodiode (PD1). Signal and drive waves with orthogonal linear polarizations were superimposed on the polarization beamsplitter BS2. After spatial filtering in a 50-cm long single-mode optical fiber, the pump and signal waves were sent through a 5-cm long Rb cell at room temperature. The external magnetic field at the cell was reduced to 10 mG level using a $\mu$-metal shield. Maximum powers of the drive and the signal waves at the cell were 0.15 mW and 0.04 mW respectively. A double balanced mixer (DBM) was used as a phase detector. The voltage-to-phase response of the DBM was calibrated introducing known delays between the two inputs. A lock-in amplifier was used for signal processing.

FIG. 2. Experimental setup.

Experimental spectra of the probe phase variation on transitions from the two ground state hyper-
fine levels (at the same conditions) are shown in Fig.3a. Around \( \delta = 0 \) the phase variations have opposite slope signs corresponding to opposite signs of the dispersion. The line shapes are in reasonable agreement with the spectra calculated for motionless atoms and single closed transitions (Fig.1). This agreement may seem rather surprising since in the experiment, due to the velocity distribution, three different atomic transitions, one closed and two open contribute to the signal in each case. On all open transitions as well as on the closed \( F_g = 1 \rightarrow F_e = 0 \) transition EIT occurs and consequently the dispersion is normal. Only on the \( F_g = 2 \rightarrow F_e = 3 \) transition EIA takes place and the dispersion is anomalous [12]. However, due to optical pumping the signal is essentially determined by the closed transitions resulting in the qualitative agreement with the theoretical prediction. To compare quantitatively the experimental spectra with theory, velocity distribution, excited state hyperfine splitting and optical depopulation of open transitions should be taken into account.

The value of \( \Delta n = c \delta \Phi / \omega l \) can be obtained taking into account the cell length \( (l = 5 \text{cm}) \). The error in the measured absolute value of the refractive index and the dispersion was around 15%. However, the reproducibility of relative measurements was within 2%.

In the following, we investigate the intensity dependence of the steep anomalous dispersion. Experimental spectra of the refractive index for different values of the drive intensity are shown in Fig.3 b. \( |I_d| \) was varied from 0.005 mW/cm\(^2\) to 0.05 mW/cm\(^2\) by using filters while the light diameter in the cell was 1.6 cm. At such low intensities \( \Delta n \) and \( D \) are growing linearly with intensity. In this case, the refractive index can be characterized by a nonlinear Kerr coefficient \( n_2: [n = n_1 + n_2 |I_d|] \). Notice that the value of \( n_2 \) is a rapidly varying function of \( \delta \). At \( \delta = 16 \text{ kHz} \) we have \( n_2 \simeq 8 \times 10^{-3} \text{ cm}^2/\text{W} \). The maximum observed dispersion at low drive intensity was \( D_{\text{max}} \simeq -6 \times 10^{-11} \text{Hz}^{-1} \).

Based on the previous considerations, the attempt was made to maximize the dispersion by increasing the drive intensity. Because of laser power limitation, the increase of \( |I_d| \) was obtained through light cross-section reduction using a telescope. For three different diameters (1.6, 1.0 and 0.6 cm), the drive wave attenuation resulted in dispersion reduction (Fig.4) indicating that we were in the region below the maximum of the dependence \( D(I_d) \). The absolute values of \( D \) and \( n_2 \) were reduced \( (n_2 \simeq 2 \times 10^{-3} \text{ cm}^2/\text{W} \) and \( n_2 \simeq 5 \times 10^{-4} \text{ cm}^2/\text{W} \) for 1.0 cm and 0.6 cm drive beam diameter, respectively) in spite of the fact that the intensity was higher. However, we should notice that the light cross-section reduction results in a shortening of the interaction time. The observed reduction of the dispersion for smaller beam diameters indicates that the role of the interaction time is essential. Only at light wave diameter close to 0.4 cm we were able to reach a maximum in the \( D(I_d) \) dependence. At relatively high intensity \( (|I_d| > 1 \text{ mW/cm}^2) \) the dispersion decreases with drive intensity and the refractive index profile becomes significantly different from a dispersion function (see inset of Fig.4). We noticed that within some range of intensity, \( D \) (around \( \delta = 0 \)) is almost independent on \( |I_d| \), while the spectral distance between extrema of \( n(\delta) \) is growing with \( |I_d| \). This distortion reflects the influence of different time constants. The precise comparison with theory requires a detailed consideration of the transient behavior of the coherent medium.

**FIG. 3.** a) Phase resonances for laser frequencies corresponding to the transitions \( 5S_{1/2}(F_g = 2) - 5P_{3/2}(F_e = 3) \) and \( 5S_{1/2}(F_g = 1) - 5P_{3/2}(F_e = 0) \) of \(^{87}\text{Rb} \) (beam diameter: 0.8 cm, drive intensity: 0.3 mW/cm\(^2\)). b) Refractive index for the transition \( 5S_{1/2}(F_g = 2) - 5P_{3/2}(F_e = 3) \) as a function of \( \delta \) for different values of \( |I_d| \) and beam diameter 1.6 cm.

It is possible to characterize a dispersive medium by a light group velocity \( V_g = c/(n + \nu \times dn/d\nu) \). Steep dispersion \(( |dn/d\nu| \gg |n/\nu| \) is intimately associated with large group velocity near the resonance. The maximum obtained value of steep anomalous dispersion \( D_{\text{max}} \simeq -6 \times 10^{-11} \text{Hz}^{-1} \) corresponds to a rather slow negative group velocity \( V_g \simeq -c/23000 \). It is interesting to mention that the value of \( V_g \) can be infinitely large with opposite signs at relatively low anomalous dispersion \(( dn/d\nu \simeq -n/\nu \simeq -2.6 \times 10^{-15} \text{Hz}^{-1} \) \). According to the linear fits on Fig.4 this can be easily obtained with
a very weak drive intensity $I_d \sim 10^{-5}$ mW/cm$^2$. Also in our case a wide range group-velocity variation can be achieved by switching between normal and anomalous dispersion (selecting the atomic transition) and/or varying the drive intensity.

FIG. 4. Measured dispersion for different beam diameters $\varnothing$. Squares: $\varnothing = 1.6$ cm, Circles: $\varnothing = 1.0$ cm, Hollow triangles: $\varnothing = 0.4$ cm. The laser frequency was locked to the Doppler-free resonance on the $5S_{1/2}(F_g = 2) \rightarrow 5P_{3/2}(F_e = 3)$ transition. Inset: Refractive index as a function of $\delta$ for $\varnothing = 0.3$ cm and different intensities. Solid line: $I_d = 0.2$ mW/cm$^2$. Dotted line: $I_d = 2$ mW/cm$^2$.

Large dispersion is interesting for different applications. Several ways, in addition to optimizing $I_d$, can be considered to increase the dispersion (both normal and anomalous) in degenerate two-level systems. Since $n$ and $D$ are proportional to the atomic density while the resonant medium is thin, it is possible to obtain higher dispersion at higher $N$. In an optically thick medium, thanks to EIT, further increase of normal dispersion is possible [15]. Another possibility is to use a medium with very slow ground state relaxation, for instance in a cell with buffer gas [16] or a cell with an anti-relaxation coating [17]. According to Eq. 1 one can expect that in this case less intensity is needed to reach the maximum of the $D(I_d)$ dependence ($\Omega^2_{\text{max}} \sim \gamma \Gamma/2$).

Coherently prepared media with optically controlled dispersion can be of interest for the design of new devices for pulse delaying/compressing in communication systems and optical computing. Also, the use of steep magnetically dependent dispersion for high precision magnetometry was discussed in detail [18]. We should notice, however, that the requirements on the coherent medium are somehow different for these applications. For pulse processing elements the bandwidth should be rather wide to permit operation with short pulses. On another hand higher sensitivity for low frequency variations of magnetic field require narrow resonances. Steep dispersion on driven degenerate two-levels systems appear suitable for the two types of applications.

In conclusion, we have demonstrated for the first time, in agreement with the theoretical prediction, steep normal and anomalous dispersion in a driven degenerate two-level atomic system. This result clearly stresses the importance of degenerate two-level systems for the investigation of quantum coherence and applications.

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