Characteristics of absorption and dispersion for rubidium D_2 lines with the modulation transfer spectrum

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Abstract: Absorption and dispersion signals of D_2 lines of rubidium atoms in a vapor cell have been experimentally investigated with the modulation transfer spectrum (MTS). Normal dispersion was observed at the transitions of $F_g \rightarrow F_e = F_g - 1$ and $F_g \rightarrow F_e = F_g$; anomalous dispersion, at transitions of $F_g \rightarrow F_e = F_g + 1$; and crossover resonance, by the transitions of $F_g \rightarrow F_e = F_g - 1$ and $F_g \rightarrow F_e = F_g$. The signal lineshape of the MTS and the detector phase are addressed accurately.

OCIS codes: (020.1670) Coherent optical effects; (020.2930) Hyperfine structure.

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With the modulation transfer spectrum (MTS), the modulation of a pump beam can be transferred to a counterpropagating (and originally unmodulated) probe beam in a nonlinear medium [1]–[5]. Modulation transfer occurs because the probe and two frequency components of the modulated pump, such as the carrier and one sideband, undergo four-wave mixing as a result of the nonlinear susceptibility of the medium. If the susceptibility is sufficiently strong, this interaction produces a fourth beam, which, in the case of counterpropagating pump and probe beams, is a sideband for the probe. The sidebands generated in the probe field and the probe field itself produce a photocurrent at the modulation frequency in a photodetector. By use of a phase-sensitive detection scheme, it is therefore possible to recover the dispersion and absorption components of the subresonance related to the in-phase and quadrature-demodulated components, respectively. These signals are odd functions of the frequency detuning between the laser frequency and the resonance frequency. Because modulation transfer is a purely nonlinear phenomenon, it is insensitive to the background absorption of the medium and is consequently particularly well suited to applications in which one wishes to lock a laser to a well-defined frequency reference. The applicability of the MTS in the laser frequency standards has been well demonstrated during the past couple of years in frequency-doubled YAG lasers, which are precisely stabilized to the molecular iodine transitions [6], [9]. The MTS method has also been used on the Rb [10] and Cs [11] atomic species for applications in metrology. It has been pointed that the intensity relationship of the signals obtained by the MTS in different transitions is different from that in the absorption spectrum signals [10], [11], but this phenomenon has not been explained so far. The usual technology in the MTS via saturated absorption centers on using frequency modulation (FM) to produce the sidebands on the pump beam. This is primarily because in practice it is relatively simple to frequency modulate a beam at high frequencies with electro-optic modulators. High frequencies are desirable because the laser amplitude noise is reduced, which allows better signal-to-noise ratios. However, when the modulation frequency is lower than the sub-Doppler linewidth, both the absorption and the dispersion signals have a high slope which crossed the center of the resonance (frequency discriminator) and can therefore obtain optimum signals for laser frequency locking to the resonance center.

In this paper, we experimentally investigate the absorption and dispersion signals of Rb D_2 lines in a vapor cell with the MTS. The pump-saturating beam is frequency shifted by 110 MHz and, at the same time, is frequency modulated (100 kHz) with an acousto-optic modulator (AOM). A lock-in amplifier is employed to demodulate the signal of the MTS accurately at different detector phases. The anomalous and normal dispersions in coherently prepared degenerate two-level atomic transitions has been observed. The maximum signals of the MTS as well as the corresponding detector phases are given. To the best of our knowledge, this is the first experiment using the MTS to investigate the characteristic of absorption and dispersion of Rb. The signal strength of the MTS at different atomic transitions is also analyzed.

The MTS is generally observed by means of detecting the beat between the probe field and the induced sidebands with a phase sensitive detector. When a frequency-modulated pump beam is used, the beat signal on the detector is of the form [1]

$$\begin{aligned}\text{signal} \quad = \quad & \frac{1}{\sqrt{\Gamma^2+\omega_m^2}}\sum_{n=-\infty}^{\infty} J_n(\beta)J_{n-1}(\beta) \\ & \times[C(L_{(n+1)/2}+L_{(n-2)/2})\cos(\omega_m t+\phi) \\ & +B(D_{(n+1)/2}-D_{(n-2)/2})\sin(\omega_m t+\phi)], \end{aligned} \tag{1}$$

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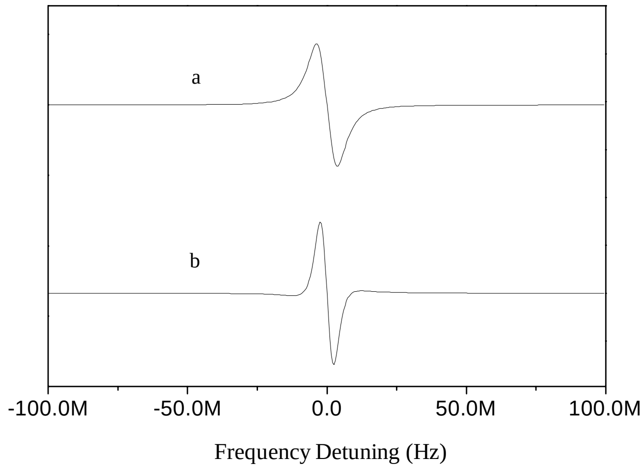

Fig. 1. Absorption X (curve a) and dispersion Y (curve b) lineshapes of the MTS for $\omega_m < \Gamma, \beta < 1$. $\Gamma = 5$ MHz and $\omega_m = 2$ MHz.

where $L_n = \frac{\Gamma^2}{\Gamma^2+(\omega-\omega_0+\Delta/2+n\omega_m)^2}$ is the Lorentzian function describing the absorption and $D_n = \frac{\Gamma(\omega-\omega_0+\Delta/2+n\omega_m)}{\Gamma^2+(\omega-\omega_0+\Delta/2+n\omega_m)^2}$. Here J_n is the nth-order Bessel function, β is the modulation index (the ratio of the modulation depth to the modulation frequency), Γ is the natural line width, ω_m is the modulation frequency, Δ is the frequency shift between pump and probe beams, $\omega - \omega_0$ is the frequency detuning from line center, and ϕ is the detector phase with respect to the modulation field applied to the pump beam. C and B are constants that depend on the properties of atomic transitions. When the modulation frequency ω_m is lower than the sub-Doppler linewidth Γ, the absorption lineshape (in-phase component) of the MTS is a dispersion-like signal that is proportional to the derivative of the original absorption lineshape of the driven two-level atomic transitions versus the frequency, and the dispersion lineshape (in-quadrature component) is just the original dispersion lineshape of the atomic transitions as shown Fig. 1. Both the absorption and dispersion signals show the same lineshape and have a high slope crossing the center of the resonance. Thus Eq. (1) is simplified to

$$\text{signal} = X\cos(\omega_m t + \phi) + Y\sin(\omega_m t + \phi). \tag{2}$$

From Eq. (2), the maximum signal amplitude is obtained at $\tan(\phi) = Y/X$. Phase angle ϕ may be adjusted accurately owing to use of the lock-in amplifier in our experiment, so in-phase component X and in-quadrature component Y may be measured, respectively.

The experimental setup for the MTS is illustrated in Fig. 2. Two Faraday isolators (40 dB) in series are placed in the output of a master-oscillator power amplifier (MOPA) semiconductor laser system (TuiOptics TA100) in order to avoid optical feedback. A small percentage (B_2) of the output beam ($\sim$1 mW) is picked off by a beam splitter (BS) for the MTS, which is then is separated by a polarizing beam splitter (PBS1) into parts 1 and 2. The beam 1 ($\sim$0.3 mW) and beam 2 ($\sim$50 µW) serve as the pump and probe lights for the MTS of Rb atoms, respectively. The two beams collinearly counterpropagate in a 3-cm-long Rb glass cell. The Rb cell is magnet-shielded with a µ-metal shielding. To reduce the disturbance of the optical feedback from the photodetector to the MTS, the pump beam is frequency shifted by 110 MHz with an AOM (Crystal Technology, Inc., Model 3110). Unlike ordinary MTS technology in which the pump beam is phase modulated by means of an EOM, in our scheme the frequency modulation is also implemented with the same AOM. The voltage-controlled oscillator (VCO) with the dc offset control voltage is used to produce the rf output at 110 MHz. A small (60 mV, 100 kHz) sinusoidal oscillation is added on the VCO control voltage, which forms a frequency modulation of ±180 kHz on the pump beam. The sidebands generated in the probe field and the probe field itself are detected by a PIN photodiode detector (PD) after passing through the polarized beam splitter (PBS2). A lock-in amplifier (Stanford Research Systems Model: SR830 DSP) phase-sensitively demodulates this beat signal to provide dispersion-shaped MTS signal. The saturated absorption signal is observed simultaneously by means of dividing a part of the photocurrent from the detector on an oscilloscope.

Figure 3 shows the recorded spectra on the oscilloscope when the frequency of the laser diode is scanned over the transition $F_g = 3 \rightarrow F_e$ of the D_2 line of ^{85}Rb (780nm) for the different polarizations (90°, $\sim$ 60°, and $\sim$ 40° with respect to the polarization of the pump light) of the probe beam, in which the saturated absorption signal and the in-phase and in-quadrature components of the MTS are simultaneously recorded. From comparison among the upper traces of Figs. 3(a)–3(c) it can be seen that the saturated absorption signal of $F_g = 3 \rightarrow F_e = 4$ is changed from positive peak (enhanced transmission) to negative peak (enhanced absorption) when the angle between probe and pump beam polarizations are changed from orthogonal to parallel. Similar peculiarities in the saturated absorption lineshapes have been studied in previous papers [12], [13]. Optical pumping of the pump beam increases the dipole coupling strength of probe beam with the same polarization and is therefore responsible for the increase in absorption. Conversely, the probe beam orthogonal to that of pump beam counteracts this pump process, leading to a decrease of the effective dipole moment and hence an increase in transmission. The middle traces of Figs. 3(a)–3(c) are the in-phase component X of the MTS whose amplitude and sign for the transition $F_g = 3 \rightarrow F_e = 4$ sensitively depended on the saturated absorption signal.

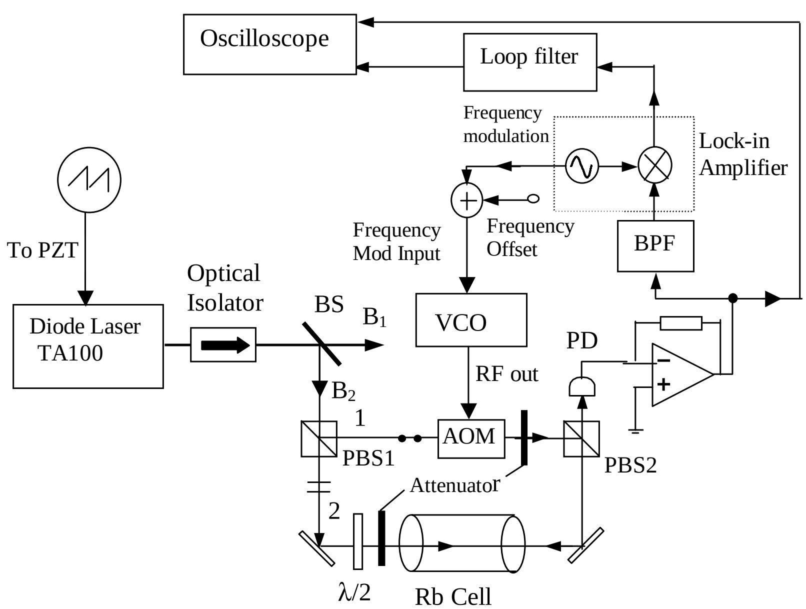

Fig. 2. Experimental setup for the MTS of Rb. BPF, bandpass filter; BS, beam splitter; PBS, polarizing beam splitter; VCO, voltage-controlled oscillator; AOM, acousto-optic modulator; PD, photodiode.

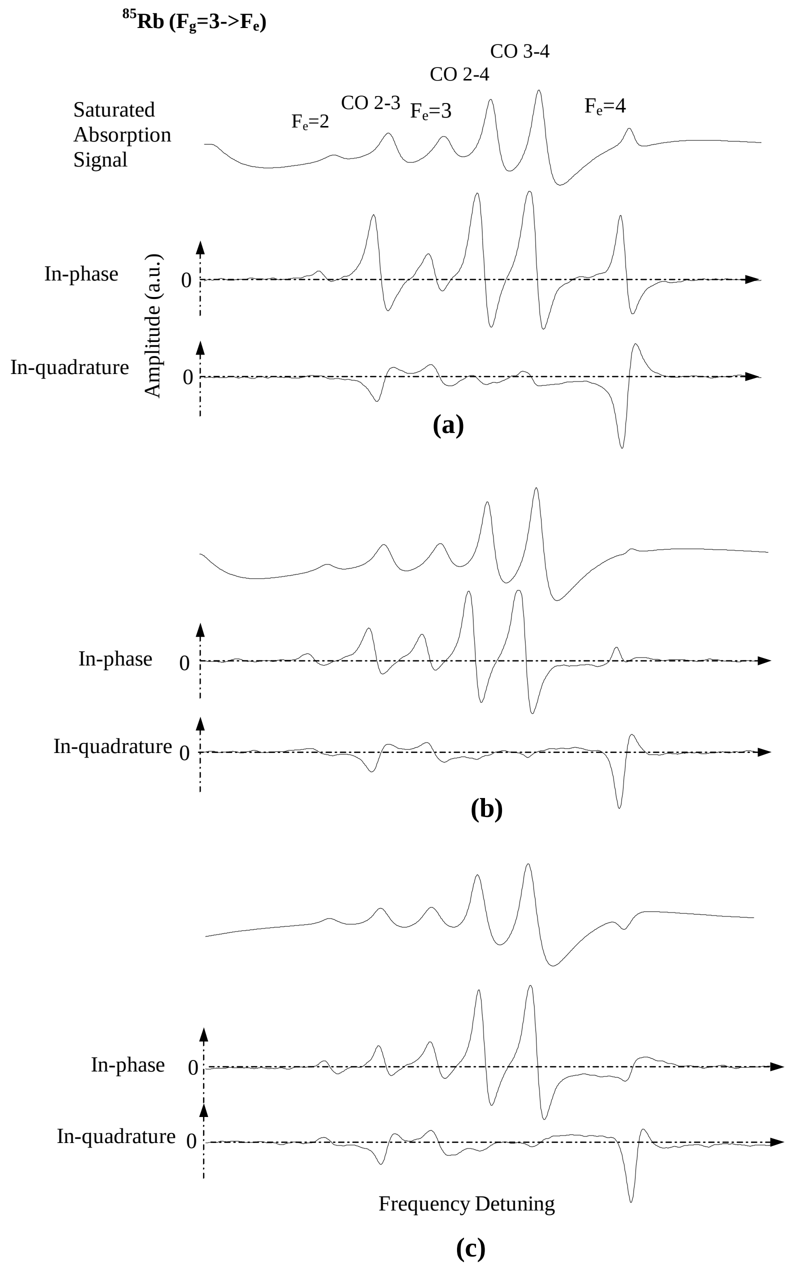

Fig. 3. Spectra when the laser-diode frequency is scanned over the transition $F_g = 3 \rightarrow F_e$ of the D_2 line of ^{85}Rb for various polarizations of the probe beam. The linear polarization of pump beam is in the vertical direction. (a) Linear polarization of the probe beam is perpendicular with that of pump light. (b) Linear polarization of the probe beam is at ˜60° with respect to that of pump beam. (c) Linear polarization of the probe beam is at ˜40° with respect to that of pump beam. The transitions are identified at the top of diagram (a): “CO3-4” for the crossover resonance between the 3→3 and the 3→4 transitions.

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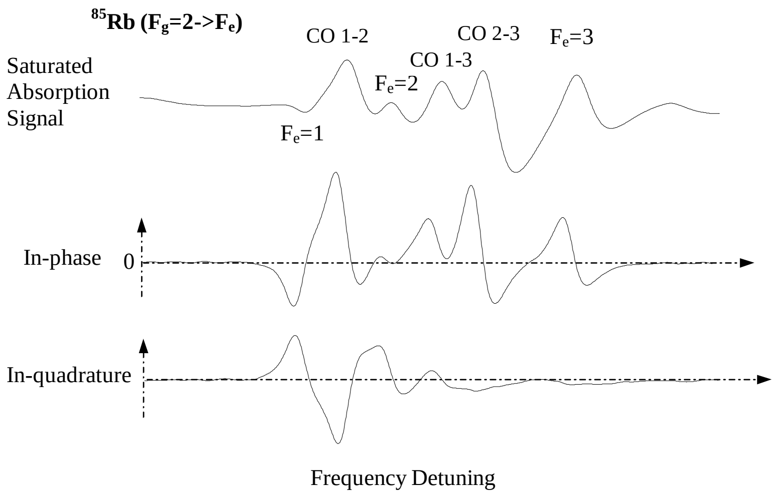

Fig. 4. Spectra when the laser-diode frequency is scanned over the transition $F_g = 2 \rightarrow F_e$ of the D_2 line of ^{85}Rb. The linear polarizations of the probe beam are perpendicular to those of pump beam.

The in-quadrature (dispersion) components Y of the MTS in Figs. 3(a)–3(c) are independent on the saturated absorption signal. The closed transition $F_g = 3 \rightarrow F_e = 4$ has larger anomalous dispersion than the open transition $F_g = 3 \rightarrow F_e = 2$ and $F_e = 3$. Although the steep anomalous dispersion in a coherently prepared degenerate $F_g = 3 \rightarrow F_e = 4$ two-level ^{85}Rb atomic system were given with a model recently used to study subnatural electromagnetically induced absorption (EIA) resonances [14],[15], our experimental results demonstrate this characteristic in a different way. The crossover resonance CO2-3 by the transition $F_g = 3 \rightarrow F_e = 2$ and $F_e = 3$ also has anomalous dispersion with low strength.

The spectra of the transition $F_g = 2 \rightarrow F_e$ of the D_2 line of ^{85}Rb for the probe beam with the linear polarization perpendicular to that of pump beam are shown in Fig. 4. The saturated absorption signal of the closed $F_g = 2 \rightarrow F_e = 1$ transition is a negative peak, thus the in-phase component X of the MTS is the negative sign. Because of the normal dispersion of the $F_g = 2 \rightarrow F_e = 1$ and $F_e = 2$ transitions [14], [15], the in-quadrature components Y have a positive sign. However, the crossover resonance CO1-2 has larger anomalous dispersion, and its in-quadrature components Y have a negative sign. In a case similar to that of the D_2 line of ^{85}Rb, the D_2 line of ^{87}Rb has the same experimental results. When we know the strength and sign of the in-phase X and in-quadrature components Y, the maximum signal strength of the MTS and the corresponding detector phase can be determined exactly.

In summary, we have experimentally investigated the absorption and dispersion signals of Rb D_2 lines in a vapor cell with the modulation transfer spectrum (MTS). When the modulation frequency is lower than the sub-Doppler linewidth, the strength and sign for the in-phase component of the MTS depend on the shape profile of the original absorption signal and for the in-quadrature component on the dispersion of the degenerate two-level atomic transitions. The normal dispersion was observed at the transitions of $F_g \rightarrow F_e = F_g - 1$ and $F_g \rightarrow F_e = F_g$; the anomalous dispersions, at transitions of $F_g \rightarrow F_e = F_g + 1$; and the crossover resonance, by the transitions of $F_g \rightarrow F_e = F_g - 1$ and $F_g \rightarrow F_e = F_g$. For the closed transitions the dispersion signal is larger. It was pointed out in Ref. [10] that the intensity relationship in the signal obtained

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by the MTS is somewhat different from that in the original absorption signal, and the authors did not present a reasonable explanation for this. From above analyses we deem that this is because, as discussed in Ref. [9], the detector phase and dispersion of the degenerate two-level atomic transitions was not considered. Our experiments shows that the transition of $F_g = 4 \rightarrow F_e = 5$ of Cs is a closed transition and has large anomalous dispersion, which results in the MTS lineshape signal of $F_g = 4 \rightarrow F_e = 5$ with an enhanced efficiency as observed in Ref. [11]. In our experiment, we use a single-passed AOM for providing the pump-beam modulation. This modulation introduces the amplitude modulation that results from pointing fluctuations of the beam. It has been observed that dispersion-shaped MTS signals are unsymmetrical as shown in Figs. 3 and 4 [5]. However, addressing the signal lineshape of the MTS accurately is important for frequency-locking applications in our research.

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