High contrast atomic magnetometer based on coherent population trapping*

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We present an experimental and theoretical investigation of the coherent population trapping (CPT) resonance excited on the D1 line of ^{87}Rb atoms by bichromatic linearly polarized laser light. The experimental results show that a lin‖lin transition scheme is a promising alternative to the conventional circular–circular transition scheme for an atomic magnetometer. Compared with the circular light transition scheme, linear light accounts for high-contrast transmission resonances, which makes this excitation scheme promising for high-sensitivity magnetometers. We also use linear light and circular light to detect changes of a standard magnetic field, separately.

Keywords: high contrast atomic magnetometer, coherent population trapping

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1. Introduction

Highly sensitive magnetometers capable of measuring magnetic fields below 1 pT are important for many applications such as geophysical surveying, space science, nuclear magnetic resonance, non-destructive testing, medical diagnoses, gravitational wave detection, etc.[1–10] We use a technique called coherent population trapping, which was discovered more than thirty years ago by Alzetta *et al.*[11] and is usually observed with a bichromatic field consisting of two resonant laser fields with the frequency difference varying in the vicinity of ground-state hyperfine splitting. At exact two-photon resonance, atoms are optically pumped into a coherent superposition of atomic ground states, which is called the dark state. The resolution of frequency measurements of the hyperfine or Zeeman resonance can be improved by increasing the coherent atom-field interaction time. A variety of techniques for increasing the interaction time in vapor cells were presented. These techniques include the use of buffer gas and the use of suitable anti-relaxation wall coatings. Further improvements in stability require the realization of coherent population trapping (CPT) resonances with optimized parameters, such as smaller line width, larger amplitude, and contrast. As is well known, in the case of the σ–σ transition scheme, a trap state insensitive to two-photon resonance exists as shown in Fig. 1. Numerous atoms are then trapped in the $|F_g = 2, m_F = -2\rangle$ state due to optical pumping and do not contribute to magnetic resonance, and only a relatively small fraction of the atoms can be pumped into a superposition state. This issue significantly limits the contrast of the magnetic resonance. In order to circumvent this unfavorable situation, different optimized excitation schemes each of which has a dark state and does not have a trap state were proposed to increase the number of atoms in the dark states. So far many sorts of excitation schemes of CPT resonances have been proposed. For example, different optimized double-lambda CPT pumping schemes such as push-pull optical pumping,[12] and the use of orthogonal circular polarizations with counter-propagating waves of $\sigma^+ - \sigma^-$ field configuration have been investigated.[13] In comparison with previous experimental configuration in atomic magnetometers by using circular polarization light,[14–17] the linear light scheme has aroused a great deal of interest in the study of atomic frequency standards. [18–21]

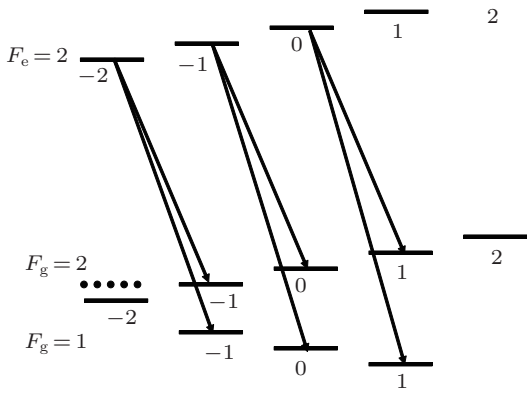


Fig. 1. Light-induced two-photon transition in a bichromatic circular field from $F_g = 1, 2$ to $F_e = 2$.

The aim of this paper is to study whether a magnetometer based on CPT using lin‖lin light is available and can be a candidate for the high sampling rate magnetometer for its high contrast signal. In this paper, we use a simple method of forming high contrast magnetic resonance with a bichromatic linear polarization light field. This method is adequate

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for the case that the total angular moments of the ground states are $F_g = 1,\ 2$ and excited state is $F_e = 1$.[19] Possible optical transitions from the $F_g = 1,\ 2$ ground state to the $F_e = 1$ excited state due to the interaction between two optical fields are shown in Fig. 2. Figure 2(a) shows four possible two-photon resonances that create atomic coherence using two linear polarized light beams, two black pairs of transition schemes representing magneto-insensitive resonances, where dark state can be given by Eq. (1); the other two transitions reflect magneto-related resonances, and the corresponding dark states are Eqs. (2) and (3), in which case, dark states exist at an exact two-photon resonance, and a trap state does not exist. This means that these two-photon resonances have a large contrast. For σ^- polarized laser fields, there are only two resonance transitions, one is magneto-insensitive, the other magneto-related, and their dark states are Eqs. (4) and (5), respectively as shown in Fig. 2(b). In this transition scheme, ground states $|F_g = 1, m_F = 0\rangle$ and $|F_g = 2, m_F = 0\rangle$ are coupled with the excited state $|F_e = 1, m_F = -1\rangle$, and these transitions destroy the dark states.

$$|\text{dark}_{\text{linear}}(0)\rangle = N\Big\{ |F_g = 1, m_F = -1\rangle - \frac{V_{+1}^{(1)} E_{+1}^{(1)}}{V_{-1}^{(2)} E_{-1}^{(2)}} |F_g = 2, m_F = +1\rangle \Big\} + N\Big\{ |F_g = 1, m_F = +1\rangle - \frac{V_{-1}^{(1)} E_{-1}^{(1)}}{V_{+1}^{(2)} E_{+1}^{(2)}} |F_g = 2, m_F = -1\rangle \Big\}, \quad (1)$$

$$|\text{dark}_{\text{linear}}(-1)\rangle = N\Big\{ |F_g = 1, m_F = -1\rangle - \frac{V_{+1}^{(1)} E_{+1}^{(1)}}{V_{+1}^{(2)} E_{+1}^{(2)}} |F_g = 2, m_F = -1\rangle \Big\}, \quad (2)$$

$$|\text{dark}_{\text{linear}}(+1)\rangle = N\Big\{ |F_g = 1, m_F = +1\rangle - \frac{V_{-1}^{(1)} E_{-1}^{(1)}}{V_{-1}^{(2)} E_{-1}^{(2)}} |F_g = 2, m_F = +1\rangle \Big\}, \quad (3)$$

$$|\text{dark}_{\text{circular}}(0)\rangle = N\Big\{ |F_g = 1, m_F = 0\rangle - \frac{V_{-0}^{(1)} E_{-0}^{(1)}}{V_{-0}^{(2)} E_{-0}^{(2)}} |F_g = 2, m_F = 0\rangle \Big\}, \quad (4)$$

$$|\text{dark}_{\text{circular}}(+1)\rangle = N\Big\{ |F_g = 1, m_F = +1\rangle - \frac{V_{-1}^{(1)} E_{-1}^{(1)}}{V_{-1}^{(2)} E_{-1}^{(2)}} |F_g = 2, m_F = +1\rangle \Big\}, \quad (5)$$

where N is the normalization coefficient, $V_{\pm m}^{n}$ is the transition matrix elements, n is the total angular moment of ground state F_g, m is the azimuthal quantum number of the ground state, $+$ denotes the σ^+ transition, $-$ denotes the σ^- transition and E is the laser field. In order to measure the magnetic field experienced by the ^{87}Rb atoms, we detect the ground-state hyperfine splitting between two magneto-related Zeeman states using a CPT resonance. According to the Breit–Rabi formula,[22] the energy difference between two hyperfine Zeeman states in the $F_g = 1$ and $F_g = 2$ influenced by small magnetic field can be expressed approximately as $\hbar\omega_{mF_1,\, mF_2} \approx \hbar\omega_\Delta + (m_{F_1} + m_{F_2})\gamma B$, where $\hbar\omega_\Delta$ is the energy difference between the ground states $|F_g = 1,\ m_F = 0\rangle$ and $|F_g = 2, m_F = 0\rangle$, m_{F_1} and m_{F_2} are the azimuthal quantum numbers for the $F_g = 1$ and $F_g = 2$ states, respectively, γ denotes the gyromagnetic ratio of the atom, and B is the magnitude of the magnetic field. This equation embodies the main principle of the experiment. In the paper, we demonstrate that the CPT magnetometer is sensitive to a magnetic field along the direction of laser propagation.

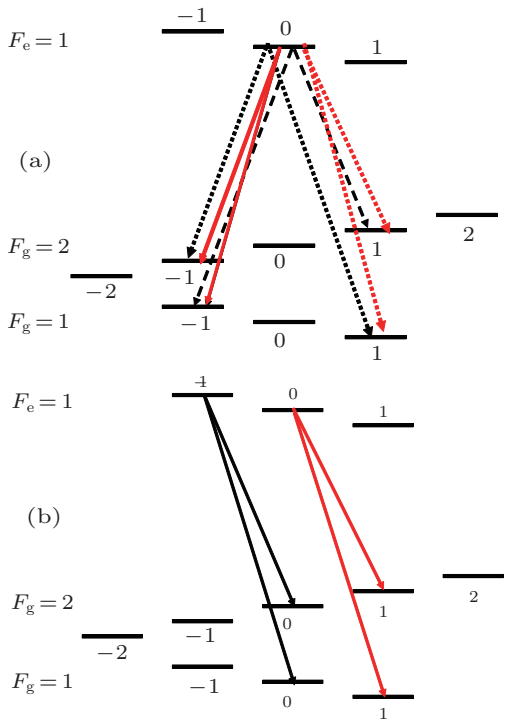


Fig. 2. (color online) Energy level diagrams of ^{87}Rb showing transition schemes: (a) lin||lin transition scheme and (b) circular–circular transition scheme.

2. Experimental procedure and results

We have demonstrated experimentally the high-contrast transmission resonance scheme with the apparatus shown in Fig. 3. A cylinder cell with a diameter of 2.5 cm and a length of 5 cm was mounted inside four layers of magnetic shields with a shielding factor of 10^6, filled with natural Rb and a buffer gas containing 1330 Pa of neon and 1330 Pa of argon to

slow the diffusion of the Rb atoms. To create sufficient atomic density in the cell, we heated it to 62 °C. A long solenoid was used to create a standard static magnetic field B and a shorter one was used to modulate magnetic field, and the magnetic fields were parallel to the light beams and normal to the flat cell wall. The light beams from two separate external-cavity diode lasers, operating at the D1 line of ^{87}Rb, and their polarizations, can be adjusted from linear ones into circular ones depending on the excitation scheme being studied. The diameter of the beam at the cell was about 7 mm, the diameters of two incident lasers were both 0.2 mW. Using an optical phase-locking system to create the bichromatic field,[23] the frequency difference between the two lasers could be precisely controlled by a local oscillator; the resonances were recorded by slowly scanning the oscillator frequency, modulating the energy level with a 3-kHz sinusoidal wave,[24] and detecting the resulting modulation of the transmitted light with a lock-in amplifier.

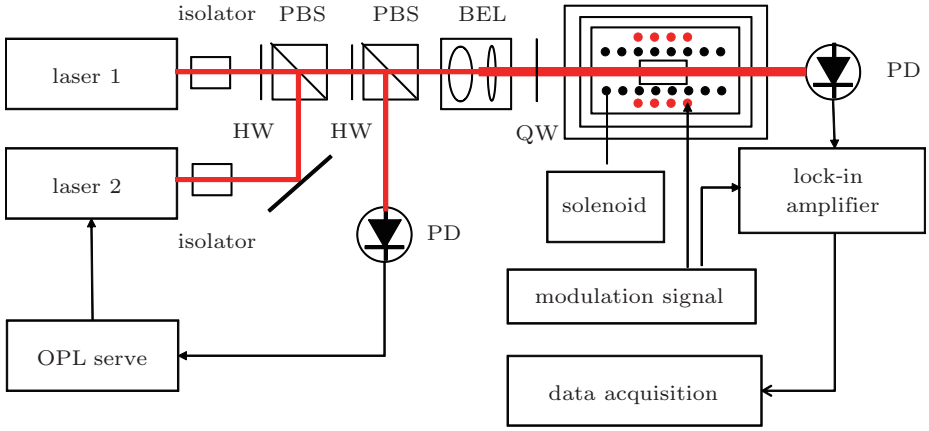


Fig. 3. (color online) Apparatus for the experimental setup; HW: half wave plate, PD: photodiode, QW: quarter wave plate, PBS: polarization beam splitter, BEL: beam expansion lenses, OPL Serve: optical phase locking serve system.

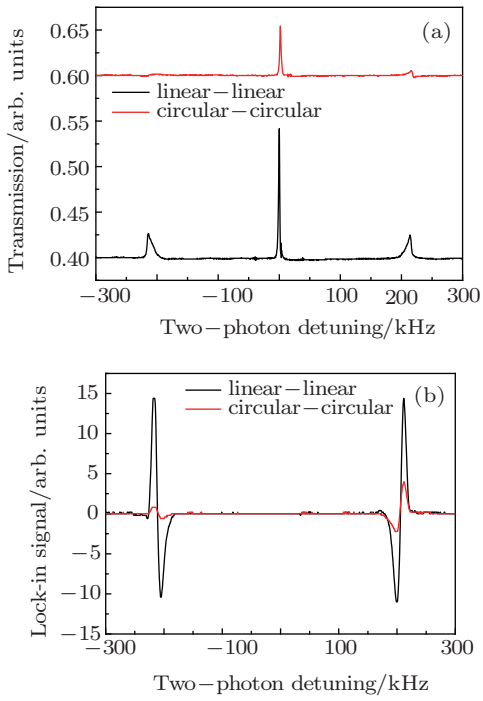


Fig. 4. (color online) The CPT resonances (a) and lock-in signal (b) for the two excitation schemes.

We performed a comparative study of two different excitation schemes of CPT resonance under the same experimental conditions. The resonance signals observed by use of two excitation schemes are shown in Fig. 4. From Fig. 4(a), it is clearly seen that the amplitude of resonance in the case of the lin||lin scheme is much larger than that in the case of circular–circular excitation, and their signal contrasts were 10% and 1.34%, respectively. The line width of the magneto-sensitive resonance is about 10 kHz. Figure 4(b) is a typical spectrum recorded from the lock-in amplifier output through an energy level modulation scheme, in which the energy levels were modulated by an AC magnetic field generated by a solenoid. Because the 0–0 transition is unaffected by the magnetic field, the lock-in signal of 0–0 transition disappeared. The amplitude of the CPT resonance in the case of the lin||lin scheme is about 5 times larger than that of circular–circular scheme.

In order to compare the magnetometer resolution abilities of the two different transition schemes, we study the two transition schemes separately. The resulting modulations from the lock-in amplifier are shown in Fig. 5, where the magnetic fields have been changed into 6.2 nT and 12.4 nT, respectively. It is clearly shown that the lin||lin scheme has a higher level of sensitivity. The lock-in time constant and sensitivity are 30 ms and 5 mV, respectively, with a filter roll of 24 dB/octave. The magnetic field used in these experiments is nominally 150 mGs (1 Gs = 10^{-4} T).

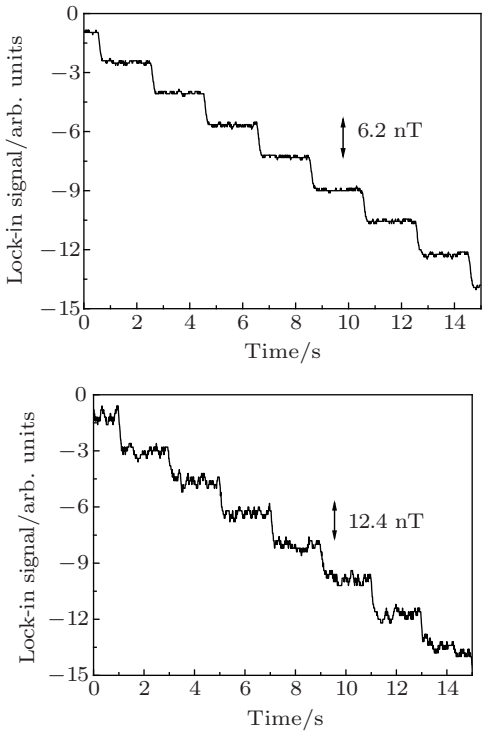


Fig. 5. Lock-in signals versus time with the magnetic field stepped in steps of 2 s.

3. Conclusions

In the present paper, we demonstrate an atomic magnetometer based on coherent population trapping operated with ^{87}Rb atoms, and with this system we investigate experimentally the behavior of a CPT magnetometer, which works with the lin||lin transition scheme. It is shown that the lin||lin transition scheme is superior to the commonly used circular–circular transition scheme. The experimental comparison with the circular–circular transition scheme indicates that the lin||lin configuration may obtain a higher contrast than general circular–circular scheme as shown in Fig. 4, and the detection sensitivity is higher than conventional scheme as shown in Fig. 5. Much more comprehensive work needs to be done, for instance, on the influences of laser intensity and excited states ($F_e = 2$) on signal contrast. Therefore, a lin||lin transition scheme provides a novel and promising atomic magnetometer prototype.

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