Bichromatic laser frequency stabilization with Doppler effect and polarization spectroscopy

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The interaction between polychromatic fields and atoms is an important subject in quantum optics. Frequency locking for small frequency interval multi-field is usually required in some experiments. In this letter, we experimentally demonstrate a holistic scheme for bichromatic laser frequency stabilization. Compared with traditional saturation absorption methods and complicated frequency shift schemes, offset locking for bichromatic fields is simply achieved using polarization spectroscopy and Doppler effect. Frequency locking with a wide-range asymmetry of the detuning is also shown. Our scheme makes laser spectroscopy experiments with polychromatic fields more convenient.

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In recent years, phenomena associated with two-level atoms driven by strong polychromatic fields have been widely studied theoretically and experimentally[1−4]. Polychromatic excitations in coherent photon-atom interaction have also been studied experimentally by several groups[5,6]. Polychromatic electromagnetically induced transparency (EIT) is one of the research interests in nonlinear optics and quantum optics. It is a potential candidate for slowing photons with different frequencies[7,8]. Further and detailed investigations, such as phase-dependent absorption spectral features, fluorescence emission, and multiple coherent population trapping (CPT) resonances[9−11], will enable more sufficient control of light. Deep and wide experimental studies in this field have benefited from the development of laser systems and related optical devices. Coherent polychromatic fields with small frequency separation and high power can be generated by one diode laser and some optical modulators.

Complexity, however, may be introduced in experiments with even fields. In bichromatic excitations, for example, two strong laser beams are produced by acousto-optical modulators (AOMs) with modulation frequency $\Delta\nu$. In the experiments, the two fields should be blue and red, and detuned from resonance. To lock the laser system, an additional AOM with modulation frequency $\Delta\nu/2$ has to be used to generate a third laser beam. Apart from the complex experimental setup, phase locking for the two AOMs is needed to maintain coherence of the laser fields, and one has to suffer the loss of laser power. Moreover, if $\Delta\nu$ is small, 40 MHz for example, it is difficult to find a suitable AOM with modulation frequency $\Delta\nu/2$. All these make the experiments complex and expensive.

In this letter, we demonstrate another strategy for simplifying the laser frequency stabilization scheme. The major advantage of our method is obtaining precise and stable frequency offset at the lowest cost. To save power and eliminate possible noise, we avoid using AOM for offset locking. Figure 1 shows the main idea of the scheme. The frequency difference $\Delta\nu$ between two lights is much smaller than the light frequency, so the amplitudes of the two wave vectors are approximately equal, $|k_1| \approx |k_2| = |k|$. There are three group atoms that interact with two fields. When the frequencies of bichromatic fields are $\omega_1 = \omega_0 - \frac{\Delta\nu}{2}$ and $\omega_2 = \omega_0 + \frac{\Delta\nu}{2}$, the two lights will be resonant with the same group atoms, as shown in Fig. 1(b). Here, ω_0 is the atomic transition frequency. This configuration is similar to the mechanism of crossover in saturation absorption spectroscopy[12−14]; only atoms with special non-zero velocity contribute to the spectrum, and the center frequency of the absorption peak shifts to the middle of the two fields' frequency difference. It is a convenient method to lock laser frequency to an off-resonant site of the absorption peak of atoms, as long as the site is within the Doppler broadening[15]. The advantage of the method is that both the +1 and the −1 order diffracted beams can be used

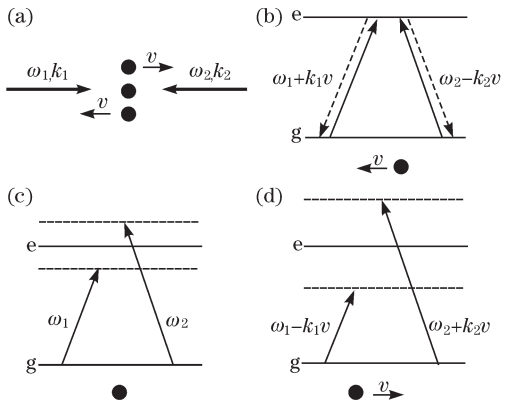

Fig. 1. Three group atoms with different velocities v, 0 and $-v$ interact with counter propagation bichromatic fields ω_1, ω_2. (a) Main idea of the scheme, (b) velocity group is in resonance with both fields, (c) neither of the two fields is in resonance with the zero velocity group atoms, and (d) velocity group makes the two fields detuned far from resonance.

to stabilize the laser frequency at the same point. In this case, one needs to choose different group atoms moving in the opposite direction but with the same velocity. This property helps us extend the dynamic range of frequency stabilization.

Polarization spectroscopy is applied for error signals[16−24]. It is a type of Doppler-free spectroscopy sensitive to the refractive index of the medium. A circularly polarized pump beam saturates the atomic medium. Since only the transitions with different magnetic quantum number $\Delta m_{\rm F} = +1$ or $\Delta m_{\rm F} = -1$ are driven, the pump beam introduces optical anisotropy to the medium. Another linearly polarized probe beam is then sent through the medium from the opposite direction. A linearly polarized light can be decomposed into two circularly polarized components. As long as the probe beam is weak enough, the two components could be considered separately. Due to the pump beam, the changes of the refractive indices for the two components are different. Moreover, the polarization of the probe beam will be rotated. The rotation can be detected with two detectors after the probe beam passes through a polarized beam splitter (PBS). The differential signal of the outputs of the detectors has the same shape as the differential signal of the saturated absorption spectroscopy, so it can be applied to stabilize the laser frequency. A key point of the Doppler-free spectroscopy is that the pump beam and the probe beam have the same frequency, so the question of whether or not we can obtain polarization spectroscopy with the bichromatic field should be considered. In fact, the difference is that atoms with different velocities are selected under the two situations. For the monochromatic field, atoms with zero axial velocity are selected. For the bichromatic field, atoms with $\frac{\Delta\nu}{2\omega_0}c$ axial velocity are selected. When the atoms interact with the bichromatic field, the frequencies they sense are both ω_0. Therefore, the conditions of the polarization spectroscopy are all satisfied. Everything discussed above will be proven in the experiment below.

The energy level diagram of ^{87}Rb atoms driven by bichromatic fields is shown in Fig. 2. The bichromatic fields couple the D1 transition $5S_{1/2}$, F=1→$5P_{1/2}$, F′ =2 with frequency difference $\Delta\nu = 40$ MHz.

The experimental setup for bichromatic laser frequency stabilization is shown in Fig. 3. The laser beam passes through an AOM ($\Delta\nu = 40$ MHz). The 0 and −1 order diffracted beams, with the same power and orthogonal polarization, form the bichromatic fields[25]. The two

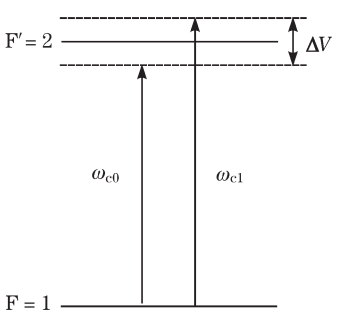

Fig. 2. ^{87}Rb atoms are driven by strong bichromatic fields. ω_{c0} and ω_{c1} are the frequencies of the bichromatic fields, and $\Delta\nu = \omega_{c1} - \omega_{c0}$.

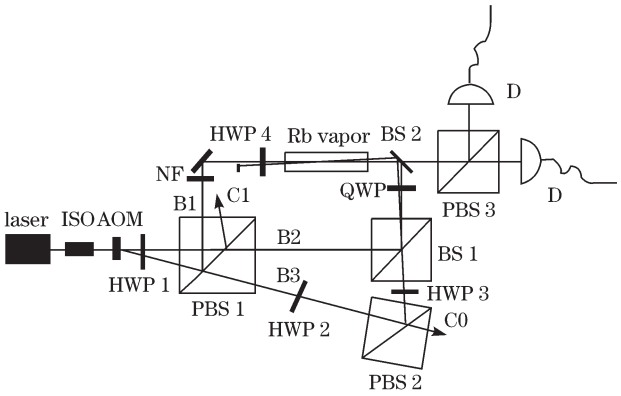

Fig. 3. Experimental setup. ISO: optical isolator; QWP: quarter wave plate; D: detector.

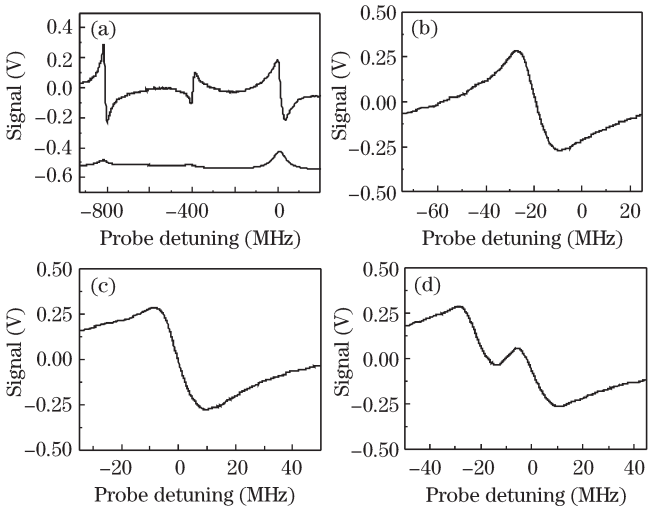

Fig. 4. Polarization spectra under different conditions. (a) Polarization spectroscopy signal of transition ^{87}Rb: $5S_{1/2}$, F=1→$5P_{1/2}$, F′ =1, 2 (the upper curve) and the saturated absorption spectrum (the lower curve), where "F′=1" is the saturation absorption peak of $5S_{1/2}$, F=1→$5P_{1/2}$, F′ =1 transition, "F′=2" stands for $5S_{1/2}$, F=1→$5P_{1/2}$, F′ =2, and "Co[1,2]" is the crossover peak. (b) The reflecting beam from PBS2 is blocked. (c) Beam B2 is blocked. (d) Both pump beams are sent to the vapor.

beams are divided into four beams by PBS1. The powers of both beams B1 and B2 are about 1 mW. Adjusting half wave plate (HWP)2 makes the power of the reflecting beam only 1 mW. The reflecting beam and beam B2 with the same polarization combine to pump the medium. After passing the neutral filter (NF), the power of beam B1 is about 30 μW. Beam B1 then passes through a 10-cm-long Rb vapor as the probe beam, which is divided by PBS3 and detected with the heterodyne method. C0 and C1 are the bichromatic fields. For the bichromatic excitation experiments without asymmetrical detuning, one does not need the reflecting beam from PBS2. With the reflecting beam, the laser could be locked for the bichromatic field with asymmetrical detuning.

For comparison, we first measured the polarization spectrum and the corresponding saturated absorption spectrum of the transition ^{87}Rb: $5S_{1/2}$, F=1→$5P_{1/2}$, F′ =1, 2, as shown in Fig. 4(a). Here, as a usual frequency stabilization scheme, the pump beam and the

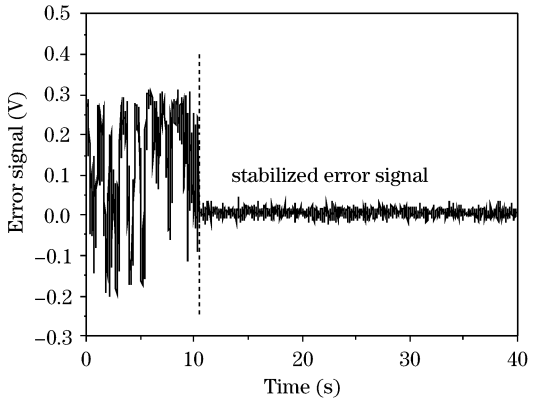

Fig. 5. Error signals before and after the laser frequency are stabilized.

probe beam have the same frequency. To avoid confusion, the related experimental setup is not drawn. Therefore, one of the bichromatic fields is in resonance with atoms when the laser is locked, which is not suitable for the experiments with bichromatic excitation. Now, we turn to our scheme in Fig. 3. We consider three situations here. Firstly, when only the reflecting beam from PBS2 is blocked, the polarization spectrum is shown in Fig. 4(b). If we lock the laser at the center of the spectrum, the frequency of the −1 order beam is ω_0-20 MHz and that of the zero order beam is ω_0+20 MHz. Secondly, when only beam B2 is blocked, the polarization spectrum is shown in Fig. 4(c). If we lock the laser at the center of the spectrum, the frequency of the −1 order beam is ω_0 and that of the zero order beam is ω_0+40 MHz. Thirdly, when both of the pump beams are sent to the vapor, the polarization spectrum is shown in Fig. 4(d). If we lock the laser with the spectrum, the frequency range of the −1 order beam is from ω_0-20 MHz to ω_0, and the corresponding range of $\frac{\omega_{c0}+\omega_{c1}}{2}$ is from ω_0 to ω_0+20 MHz. The bichromatic field can clearly be locked without additional AOM. In the scheme, the frequency center of the bichromatic field $\frac{\omega_{c0}+\omega_{c1}}{2}$ can be modulated with a negative detuning, which is feasible for asymmetry bichromatic excitation. To expand the range of $\frac{\omega_{c0}+\omega_{c1}}{2}$, we can change the role of the 0 and −1 order diffracted beams; $\frac{\omega_{c0}+\omega_{c1}}{2}$ will then change from ω_0-20 MHz to ω_0.

In evaluating the performance of the scheme, we record the error signal of the laser, as shown in Fig. 5. The recording time is 40 s. The laser frequency varies in a wide range when it is free-running. With good magnetic shielding, the typical capture range for the laser is about 10 MHz with polarization spectroscopy. Compared with Fig. 4(a), the error signal for the laser is only one-tenth of a voltage range standing in capture range after being locked. Hence, the laser has a stable frequency below 1 MHz.

In conclusion, we experimentally realize the stabilization of bichromatic laser frequencies. Offset locking for the bichromatic field is simply achieved using polarization spectrum and Doppler effect. Phase noise from additional devices and laser power loss is avoided using the Doppler effect. Polarization spectrum is used for error signals, and for suppressing noise. The method can be easily extended to any experiment using polychromatic laser fields.

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