Nonlinear enhanced-absorption resonances in compact alkali-vapor cells for applications in quantum metrology

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Abstract. We review three laser spectroscopy schemes developed recently for observation of high-contrast enhanced-absorption nonlinear resonances in small alkali-vapor cells. In our experiments, optical transitions within the cesium D\textsubscript{1} line are involved and a probe beam transmission is analyzed. The first spectroscopy method is based on the configuration with two-frequency counter propagating beams, which are linearly polarized in orthogonal directions. This configuration provides observation of high-contrast natural-linewidth resonances superimposed on broad Doppler profiles when the laser frequency is scanned. These resonances have good prospects for developing a miniature optical frequency reference. The second scheme involves two-frequency counter propagating beams with equal circular polarizations and provides observation of subnatural-linewidth resonances when the Raman frequency detuning is scanned. We use these resonances for stabilizing the microwave frequency of a local oscillator (= 4.6 GHz). Frequency stability of around $6 \times 10^{-12}$ is achieved at 1-s averaging using a 5-mm length cell. This result makes the technique attractive for developing a miniature frequency standard in the microwave range. The third configuration exploits single-frequency counter-propagating beams with linear orthogonal polarizations. The ultrahigh-contrast subnatural-linewidth resonances can be observed when the longitudinal magnetic field is scanned around zero. The possible application is discussed of these resonances in vector atomic magnetometry.

1. Introduction

Atomic frequency standards (AFSs) and atomic magnetometers (AMs) have become indispensable tools for performing various interesting experiments in fundamental physics both on the ground and in space,
such as dark-matter search [1], detection of gravitational waves [2], precise measurements of fundamental constants and their temporal variations [3], search for the neutron electric dipole moment [4] and so forth. Many relevant contemporary technologies in the fields of satellite and satellite-free navigation systems, including navigation in deep space [5], very-long-baseline radio interferometry [6], geophysics [7], biology and medicine [8] have already benefited from using AFSs and AMs. Special efforts are nowadays aimed at developing miniaturized quantum devices with small weight and power consumption. Such AMs and AFSs are often based on various laser spectroscopy techniques with the usage of miniature alkali-vapor cells (see review [9]). In this regard, it is of paramount importance to choose an appropriate spectroscopy technique, which could provide high-quality reference signals in the case of small-scale cells, achieving high sensitivity of magnetic field measurements or high frequency stability.

In this paper, we summarize our results obtained in the past two years on the development of novel spectroscopy schemes for observation of high-quality nonlinear resonances in small-scale vapor cells under a cw regime of excitation. We briefly discuss the prospects of the proposed schemes for the creation of miniaturized atomic frequency standards in the microwave and optical frequency ranges and atomic three-axis magnetometers.

2. Sub-Doppler natural-linewidth resonances in two-frequency light field

The spectroscopy technique based on saturated-absorption resonances (SARs) is a well-known spectroscopy method, which helps to achieve high spectral resolution when the optical-spectrum absorption lines suffer significant Doppler broadening due to the thermal motion of atoms or molecules in a gas [10]. Usually, this method uses a light-field configuration consisting of two counter-propagating laser beams of the same frequency \( \omega_0 \). This technique is widely used in various frequency standards and many other laser-based technologies to this day (e.g., see [11-13]), including ones for space applications [14-17]. In order to get a better signal-to-noise ratio (SNR), SARs are often registered in cells of extended length, up to several tens of cm. Moreover, a multi-passage configuration is often used to reach a better performance of the SAR-based frequency standard [15, 17]. One of the most compact laser sources frequency-stabilized to SAR in rubidium vapors has been reported in [18]. It uses a compact evacuated 2-cm\(^3\) glass cell, with a measured optical frequency stability \( \sigma_f \) (Allan deviation) around \( 2 \times 10^{-12} \) at 1-s averaging. Unfortunately, the “classical” SAR technique does not demonstrate good results in miniature cells with \( V \ll 1 \) cm\(^3\).

A modernized SAR technique has been proposed in [19] for observation of high-contrast sub-Doppler resonances. The counter-propagating two-frequency laser beams with orthogonal linear polarizations were used to excite optical transitions in the cesium \( D_1 \) line in a cm-scale vapor cell (\( V \approx 6 \) cm\(^3\)). The nonlinear natural-linewidth resonances were observed in the light-field transmission as absorption spikes superimposed on broad Doppler profiles. As qualitatively explained in [20], the high-contrast resonance effect was linked to coherent population trapping (CPT) [21]: low-light-field absorption takes place in the cell at large optical frequency detuning owing to CPT, while absorption becomes very strong at the center of the resonance curve because a CPT state cannot be created under the conditions considered. It was proposed then to use a two-frequency technique for the development of a miniature optical frequency reference [22]. In particular, the measured optical frequency stability was around \( 2 \times 10^{-12} \) at 1 s using a micro-cell with a spectroscopy volume of only 5 mm\(^3\) [23].

Here, we report the results obtained with a new compact package involving a cubic small-scale glass cesium-vapor cell (\( V \approx 0.1 \) cm\(^3\), see figure 1 (a). The cell is placed inside a heating chamber made of copper and a permalloy magnetic shield (the detailed design will be presented elsewhere). The experimental setup is sketched in figure 1 (b). A distributed Bragg reflector (DBR) diode laser (\( \lambda \approx 894.6 \) nm) and a fibered Mach–Zehnder amplitude electro-optical modulator (MZ EOM, iXBlue NIR-MX950-LN-20) are used to obtain a two-frequency light-field configuration (the carrier frequency \( \omega_0 \) is suppressed). The position of the retro-reflecting mirror (M) relative to the cell should be properly chosen to maximize the sub-Doppler resonance height [21, 22].
In the two-frequency regime, the microwave frequency $f$ of the synthesizer equals the ground-state hyperfine splitting ($\approx 4.6$ GHz), so after the MZ EOM we get $\omega_1 - \omega_2 = 4\pi f \approx 4\pi \times 4.6$ GHz. To observe the resonance curves, the laser frequency $\omega_0$ is scanned around the middle frequency $(\omega_0_1 + \omega_0_2)/2$ of the two optical transitions $F_g=3 \rightarrow F_e=4$ and $F_g=4 \rightarrow F_e=4$ with $F_g, F_e$ being the total angular momenta of the ground and excited states of the atoms, respectively. An example of the resonance is shown in figure 2. As seen, the sub-Doppler resonance height is $\approx 2.5$ times larger than the height of the broad Doppler absorption dip. Figure 2 also contains a resonance curve in a single-frequency regime, when the microwave synthesizer is switched off and the laser frequency is tuned in resonance with the strong optical transition $F_g=3 \rightarrow F_e=4$ (both curves are shifted in $x$ direction to have a common center). We can conclude that the two-frequency regime demonstrates a much better height-to-width ratio of the sub-Doppler resonance than the single-frequency one. Furthermore, the proposed technique has a relatively simple architecture in comparison, for instance, with another advanced technique proposed recently in [24]. Therefore, we believe that the proposed two-frequency method has good prospects for developing a miniature optical frequency standard.

![Figure 1](image1.png)

**Figure 1.** (a) Evacuated cubic glass cell filled with cesium atoms. (b) Scheme of the experimental setup for two-frequency sub-Doppler spectroscopy: DBR – distributed Bragg reflector diode laser, OI – Faraday optical isolator; $\lambda/2$ and $\lambda/4$ – half-wave and quarter-wave plates, respectively; PBS – polarizing beam splitter; $\mu$-synth. – microwave synthesizer; PD – photodetector.

![Figure 2](image2.png)

**Figure 2.** The resonance curves in two-frequency (pink dip) and single-frequency (blue peak) regimes. $T_{cell} \approx 45^\circ C$ in the 2-freq. regime and $\approx 60^\circ C$ in the 1-freq. regime. $P_{total} \approx 1.1$ mW, beam diameters $\approx 2$ mm. FWHM $\approx 27$ MHz in 2-freq. regime versus $\approx 58$ MHz in 1-freq regime.
3. Subnatural-linewidth EIA resonances in a two-frequency light field

CPT is a bright example of the quantum interference effect in atoms that has already found numerous interesting applications in laser spectroscopy [25], propagation of light pulses [26, 27], atomic magnetometry [8, 28, 29], etc. In atomic laser spectroscopy, CPT is usually observed as a “dark” resonance, i.e. a subnatural-linewidth spike in vapor-cell transmission when the Raman frequency detuning is scanned around zero. The dark resonance is nowadays widely used as a reference for microwave frequency stabilization in miniature atomic frequency standards (e.g., see recent works [30, 31] and review [9]). For instance, Allan deviation as small as $9 \times 10^{-12}$ at 1 s has been measured in [30] using a tiny glass-blown spherical $^{87}$Rb vapor cell of 5 mm diameter. In pump-probe light field configurations, the dark resonance is also known as electromagnetically induced transparency (EIT) [32]. The “opposite” nonlinear effect, electromagnetically induced absorption (EIA), was discovered in 1997 as a subnatural-linewidth dip in alkali-vapor cell transmission [33, 34]. Unfortunately, since its discovery, EIA has found just rare applications in physics, such as atomic magnetometry [35], “fast” light experiments [36] and some others.

We have developed a new scheme for observation of EIA under counter-propagating circularly polarized two-frequency light beams, which can be used for the development of a microwave frequency standard [37]. The experimental setup is shown in figure 3. It has a lot in common with that used in Section 2 (see figure 1 (b)). However, we now use two separate pump (control) and probe beams. A cesium vapor cell is filled with a Ne-Ar buffer-gas mixture (Ne:Ar = 20:2 Torr). The cell length is 5 mm and its diameter is 25 mm. The benefit from using an iris diaphragm (D in figure 3) in such kind of pump-probe schemes is explained in [38]. Figure 4 shows an example of the EIA resonance observed in probe-wave transmission (the output power of the light is normalized to the input power). The Raman frequency detuning $\Delta_R = \omega_1 - \omega_2 - \Delta_{\text{inh}}$ is scanned around zero (with $\Delta_{\text{inh}}$ being the frequency of the ground-state hyperfine splitting in cesium). The light beams are in resonance with the optical transitions $F_e = 3 \rightarrow F_e = 3$ and $F_e = 4 \rightarrow F_e = 3$ of the D1 line. The resonance contrast is around 2.7% at FWHM ≈ 850 Hz (full width at half maximum).

Here, we report our recent measurements of the resonance contrast-to-width ratio. As seen from figure 5 (a), it decreases with the pump wave power decrease. This means that small pump wave powers are preferable for using the EIA resonance for microwave frequency stabilization. Figure 5 (b) shows the Allan deviation measured under the same conditions as in figure 4. It is seen that a short-term frequency stability of $\approx 6 \times 10^{-12}$ can be achieved. The obtained result is highly competitive with those presented in other works with compact CPT-based standards. Therefore, we believe that the proposed scheme can be used for developing a miniature microwave frequency standard. In this connection, further studies are required to increase the long-term frequency stability (such as light shift and temperature shift investigations, etc.).

![Figure 3. The experimental setup of the EIA-based microwave frequency standard: NDF – neutral density filter; M1, M2 – two mirrors on a linear translation stage; D – iris diaphragm (see the rest of notations in figure 1 (b). An optical Faraday isolator is not shown.](image-url)
4. Subnatural-linewidth EIA magneto-optical resonances in a single-frequency light-field

The level-crossing phenomenon in an atomic ground state can drastically change the intensity of the light transmitted through a resonant medium, leading to observation of subnatural-linewidth resonances. These magneto-optical resonances are often called the ground-state Hanle effect (GSHE) [39]. The GSHE, similar to the case with two-frequency pump-probe configurations, can be observed either as electromagnetically induced transparency (EIT) [40] or absorption (EIA) [41]. The sign of the magneto-optical resonance (EIT or EIA) depends on various physical conditions, such as the structure of the atomic energy levels involved in the atom-field interaction, buffer gas collisions, influence of a microwave radiation, etc. In our previous works [42, 43], we proposed a simple and efficient technique for controlling the sign by just changing the light wave polarizations in a pump-probe configuration. That technique, in turn, has led to the development of a new method for achieving ultrahigh-contrast magneto-optical EIA resonances in buffer-gas-filled alkali-vapor cells [44]. In particular, the EIA signals registered in a probe-wave $^{87}\text{Rb}$ vapor-cell transmission reached a contrast as high as 135% with respect to the height of abroad Doppler absorption profile ($C_D$) and 29% with respect to the background light transmission ($C_{\text{back}}$) [45]. Even more striking results were recently obtained with a 2-cm long Cs vapor cell filled with 20-Torr neon buffer gas [38], namely the EIA resonance contrast values as high as $C_D \approx 1630\%$ and $C_{\text{back}} \approx 75\%$ were observed. It should be noted that these large values were accompanied by relatively small linewidths: the FWHM of the narrowest observed EIA was approximately 0.77 mG (540 Hz in the frequency domain).
In this paper, we briefly report our latest observations of EIA resonances in a Cs glass-blown cylindrical vapor cell filled with a Ne buffer gas (20 Torr). Its length is 2 cm and the diameter is 2.5 cm. The experimental setup is shown in figure 6. For shortness, we omit detailed description of the setup, which can be found in [38]. Figure 7 demonstrates the high-contrast EIA resonances obtained by the simultaneous scanning of the longitudinal magnetic field $B_z$ around zero and the laser frequency detuning from the resonance with the optical transition $F_g = 4 \rightarrow F_e = 3$ of the $D_1$ line. Such simultaneous scanning makes the EIA resonance contrast clearly visible. In particular, it can be easily deduced that $C_D \approx 430\%$ and $C_{back} \approx 87\%$ in the presented figure. It should be noted that such a large prevalence of the EIA resonance height over the Doppler profile height is a unique result for the EIA, as well as for the EIT effects under resonance conditions, since usually the subnatural-linewidth EIT or EIA resonances are accompanied by a noticeable natural-linewidth or other broad spectral features [46], even in the case of cold atoms where atomic motion effects are significantly suppressed [47].

The GSHE (EIT or EIA type) can be used in highly sensitive magnetometry, as emphasized in the pioneering works [48, 49]. The contemporary schemes of Hanle magnetometers can use circularly [35, 50, 51] as well as linearly [52, 53] polarized waves. The magnetometer can perform scalar or vector measurements. It should be noted that vector measurements are desirable in many applications, ranging...
from fundamental physics to geophysics, medicine, and biology [54]. A new perspective can be introduced in the standard Hanle schemes by using our scheme with counter-propagating orthogonally-polarized light waves, because it provides a very high contrast-to-width ratio, which could lead to an increased sensitivity of the magnetic field measurements. To perform vector (three-axis) measurements, the proposed configuration can be used, for instance, in the so-called compensation technique [51, 52] or in another technique that has been recently proposed in [55].

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