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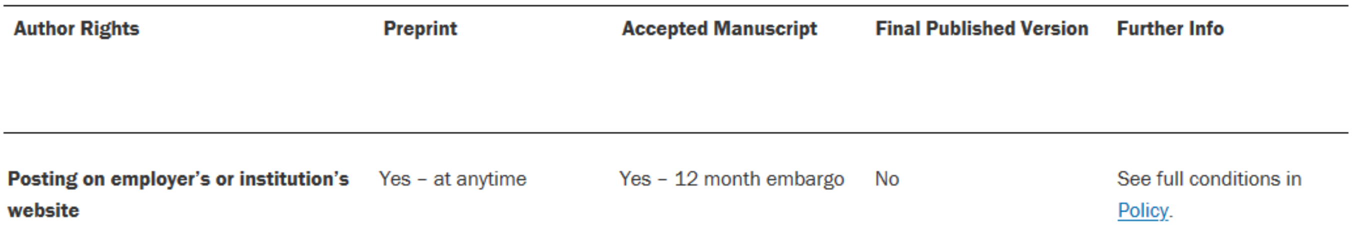

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Measurement and cancellation of light shift in optically pumped magnetometers

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Abstract –Light shift arising from the circularly polarized pump beam in atomic magnetometers can induce an undesired magnetic response, and thus affect their accuracy. Here, the light shift and the corresponding cross-talk effect in the magnetometer have been investigated, and a scheme with an additional off-resonant pump beam with an appropriate polarization and intensity has been proposed to effectively reject the light shift. And the experimental results reproduce the expected behavior. This scheme provides a powerful tool to reject the light shift in optical pumping systems, in particular, the hybrid optically pumped systems.

Introduction. – The light shift, also known as AC Stark effect, is a well-known phenomenon and normally refers to the shift of the atomic levels or transition frequencies [1, 2]. It arises from the interaction of the induced atomic dipole moment with the oscillating electric field of the laser radiation, and the shift depends on the intensity, the frequency, as well as the polarization of the light [3]. The AC Stark fluctuations constitute one of the main sources of instability not only in vapor-cell atomic frequency standards (atomic clocks) [4–6], but also in the atomic magnetometer or comagnetometer [7–11]. The magnetometer operated in the spin-exchange relaxation free (SERF) regime keeps the highest sensitivity of low-frequency field measurements [12]. However, the light shift in the SERF magnetometers can induce a response to the field in a secondary direction, an undesired cross-talk effect, and thus affect their accuracy [7].

In order to improve the accuracy of the optically pumped magnetometer, some research work has been reported to mitigate the Bloch-Siegert shift [13], while some approaches have been developed to reduce the AC Stark shift, which will be detailed in this letter. One general and straightforward method is to turn the laser to the "magic wavelength" that produces no light shift and maximize the pumping rate [14]. The zero-shift frequencies are very close to the sharp peaks of the optical absorption lines. The influence from light shift can also be suppressed by averaging two identical magnetometer configurations pumped with oppositely circularly polarized light [15]. Sulai and co-workers demonstrated the suppression of AC Stark shift by pumping a small subvolume of atoms in a low-pressure (65 torr) vapor cell [7]. However, to our best knowledge, the light shift in the hybrid optically pumped comagnetometer is still hard to be suppressed [16]. Hybrid optical pumping is a technique for producing spin polarized alkali-metal atoms A, but a second alkali-metal B is directly pumped by a circularly polarized pump and acts as the intermediary to transfer angular momentum from the laser to A [17, 18]. Compared to the scheme of conventional optical pumping, hybrid optical pumping is beneficial for a uniform polarization throughout the high-pressure (typically, greater than 500 torr) vapor cell and also yields a high spin-exchange efficiency [19, 20]. Due to the use of high-pressure cell and non-resonant intense pump beam in the hybrid pumping comagnetometer, the light shift sensed by atoms A is approximately on nT level and thus causes a serious cross-talk effect [16].

Here, the light shift and the corresponding cross-talk effect in a Cs magnetometer have been reported via the magnetic responses. A scheme, which consists of two pump beams with different laser frequency, has been proposed to reject the light shift. The elimination of the cross-talk

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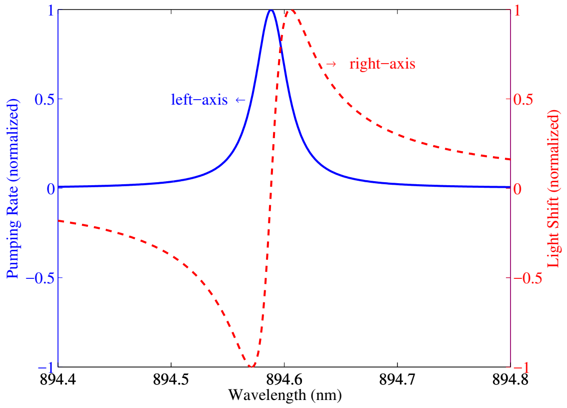

Fig. 1: Normalized pumping rate (or light absorption) and light shift as a function of the laser wavelength (D1 line of Cs). The pumping rate (blue line) is plotted against the left axis, while the light shift (red dashed line) is displayed against the right axis. Due to the pressure broadening and shift effects of He and N_2 gases, the absorption curve of D1 transition features a width of 13 GHz and is shifted to 894.588 nm, which corresponds a blue-shift of about 1.86 GHz relative to the resonance in vacuum (894.593 nm). The pressure-broadened linewidth is larger than the hyperfine splitting, therefore the hyperfine structure of both D1 and D2 lines cannot be resolved in this work. Instead, only a single absorption curve with a Lorentzian profile can be observed in our experiment.

effect in the magnetometer indicates that light-shift has been successfully suppressed. For any alkali-metal atoms, it is easy to find a second laser beam with an opposite-shifted frequency to properly compensate for the light shift arising from the first pump beam. Therefore, the approach reported here provides a powerful tool to zero the light shift in both pure and hybrid pumping systems.

Light shift in atomic magnetometer. – A pump beam with circular polarization is generally employed to create the oriented ground state, which can be used for high-sensitivity field measurement [21, 22]. For the ideal case, the optically pumped magnetometer operated in the SERF regime is only sensitive to the field B_y, expressed as

$$P_x^e \approx P_0^e \beta_y, \tag{1}$$

where the equilibrium polarization P_0^e along z axis (pump beam direction) is determined by the balance of pumping rate R_p and relaxation rate R_{rel} sensed by the alkali-metal atoms, β_y is defined as $\beta_y = \gamma^e B_y / R_{tot}^e$, $\gamma^e = g_s \mu_B / \hbar$ is the gyromagnetic ratio of free electronic spins, R_{tot}^e is the sum of R_p and R_{rel}, P_x^e is the projected component of P_0^e along x axis. However, the fictitious magnetic field along z axis L_z arising from the pump beam can induce a cross-talk effect in the SERF magnetometer, described by [7]

$$P_x^e \approx P_0^e \left(\beta_y + \beta_x \beta_z \right), \tag{2}$$

where $\beta_x = \gamma^e B_x / R_{tot}^e$ and $\beta_z = \gamma^e (B_z + L_z) / R_{tot}^e$. In Eq. (2), a nonzero coefficient β_z, which is proportional to the sum of the real field B_z and the fictitious field L_z, makes the magnetometer also sensitive to x-axis field and thus causes the undesirable cross-talk effect. This phenomenon is particularly serious in the hybrid optical pumping comagnetometers, in which case the "magic wavelength" is non-existent and the longitudinal field has been fixed [16].

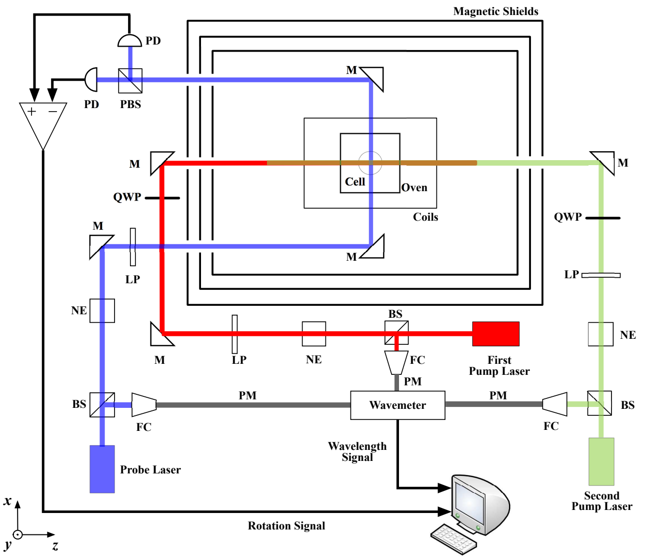

Fig. 2: Experimental apparatus. BS, beam splitter; NE, noise eater; LP, linear polarizer; QWP, quarter waveplate; M, reflection mirror; PBS, polarizing beam splitter; PD, silicon photodiode; FC, fiber coupler; PM, polarization-maintaining fiber. The first pump beam (red lines) has a right-circular polarization, while the second pump beam (green lines) features a left-circular polarization. The probe beam (blue lines) is linearly polarized to detect the rotation signal arising from the precession of the atomic spins.

When the cell is illuminated by a laser beam centered on the D1 line of the atoms, the fictitious magnetic field experienced by the atoms at high pressure features a dispersion curve, given by [14, 23]

$$L_z = \frac{-\pi r_e c f_{D1} \Phi(v)}{\gamma^e} \frac{(v - v_0)/\pi}{(v - v_0)^2 + (\Gamma_{\mathrm{L}}/2)^2} s, \tag{3}$$

where r_e is the classical electron radius, c is the speed of light, f_{D1} is the oscillator strength of D1 line, $\Phi(v)$ is the total flux of photons of frequency v incident on the atom in units of number of photons per area per time, Γ_{L} is the pressure-dependent broadening width in the presence of buffer gases [24,25], v_0 is the resonance frequency, and s is the light's degree of circular polarization. s ranges from -1 to 1, where $s = 0$ corresponds to linearly polarized π light and $s = \pm 1$ corresponds to $\sigma^\pm$ light. In Eq. (3), the light shift has a dependence on the intensity, polarization and frequency of the light, as well as the pressure broadening and shift induced by He and N_2. For a sealed vapor cell, the light shift will be proportional to the beam intensity if the light polarization and frequency were fixed.

The pumping rate and the light shift arising from a circularly polarized beam are shown in Fig. 1. The light shift features a dispersion curve as a function of the laser frequency, thus a red-shifted pump beam leads to a positive light shift, opposite to that of a blue-shifted laser beam. As the trace of pumping rate against the laser frequency is an absorption profile, both red-shifted and blue-shifted lights can be used to polarize the atoms. Therefore, it seems possible to cancel the light shift by adopting two independent pump beams without degrading the atomic polarization. Under the illumination of two pump beams, the total light shift sensed by the atoms can be added together, given by

$$L_z^{\mathrm{sum}} = L_{z1} + L_{z2}, \tag{4}$$

where L_{z1} is the fictitious magnetic field created by the first pump beam, which is the generally used in most of the cases, and L_{z2} is the virtual field generated by the second pump beam. With an appropriate choice of the polarization, intensity and frequency, the light shift arising from the second pump beam can be used to compensate for that produced by the first pump beam. In this way, the total light shift L_z^{sum} in Eq. (4) is zeroed and thus the corresponding cross-talk effect in Eq. (2) can be rejected. It is noteworthy that the detuning of the pump beam selected to cancel the light shift will be affected by the pressure broadening and shift induced by He and N_2.

Experimental apparatus. – A schematic of the experimental apparatus is shown in Fig. 2. A droplet of Cs is contained in a spherical glass vapor cell with a diameter of 10 mm. The cell is also filled with 500 torr of He gas to reduce the atom diffusions and 50 torr of N_2 gas to quench the alkali-metal excited state. The temperature of the cell is maintained at 100 °C via a boron-nitride oven heated by twisted pair cable, where ac currents with a frequency of 51 kHz are applied. The oven is housed in a 3-layer cylindrical magnetic shield made of μ-metal, providing a shielding factor of $\approx 10^6$ to quasi-static magnetic fields. A tri-axis coil is mounted inside the innermost layer of the shield, and the bias field applied along z direction is used to null the z-axis residual fields, including both the real and fictitious magnetic fields in Eq. (2).

In Fig. 2, two counter-propagating pump beams, emitted from two external-cavity diode laser systems, are used to create spin orientation in the Cs sample through optical pumping with circularly polarized light [26]. Both of the pump beams have a beam waist of about 2 mm and propagate through the cell with the same optical path. A pump light with $\sigma+$ D1 photons add angular momentum to the atoms, and over time most or all of the atoms are transferred to the $m_F = +F$ end state of $F = I + 1/2$ hyperfine level, where I is the nuclear spin. As the two pump beams enter the cell from opposite sides, they must have opposite helicity $s = \pm 1$ in order to polarize the alkali spins along the same direction. In our case, the first pump beam has a right-circular polarization while the second pump beam features a left-circular polarization. Besides, the use of counter-propagating pump beams is useful to obtain a nearly uniform pumping rate across the cell. In order to validate the feasibility of the scheme proposed here, the first pump beam is red-shifted to 894.620 nm, while the second pump beam is blue-shifted to 894.580 nm. These two pump beams correspond light detunings of approximately -12 GHz and 3 GHz, asymmetric with respect to the center of pressure-shifted D1 line. An off-resonant pump beam can lead to a nonzero light shift according to Eq. (3), and thus results in the cross-talk effect to field B_x in the Cs magnetometer. And the magnetic response is often measured by the optical rotation of a linearly polarized beam via the circular birefringence.

A probe beam with linear polarization from an distributed feedback diode laser is employed to detect the rotation signal, which is proportional to the projection of the atomic polarization along the probe beam direction. The probe beam with a positive detuning of about 200 GHz from the center of pressure-broadened D2 line propagates along x-axis and has an intensity of 8 mW/cm^2. The optical rotation of the transmitted light is measured by a balanced polarimeter set at 45° to the initial polarization, so that both outputs of the analyzer are of nearly equal intensity. A differential transimpedance amplifier (gain=$1 \times 10^7 \Omega$) is located adjacent to the photodiodes.

The laser frequency of the pump and probe beams are monitored by a wavemeter with an absolute accuracy of 60 MHz (Model WS7, HighFinesse), sufficient to conduct the experiments based on the high-pressure vapor cell. The light intensities are stabilized by the noise eaters (Model NEL03, Thorlabs) which own internal closed-loop feedbacks.

Results. – When a sinusoidal variation with an amplitude of B_x^m and a frequency of f is applied to the x-axis field component, the corresponding output with the frequency of f extracted from Eq. (2) is given by

$$P_x^e(f) \approx \frac{(\gamma^e)^2 P_0^e}{(R_{tot}^e)^2}\left[(L_z + B_z) B_x^m \sin(2\pi f)\right], \tag{5}$$

which is proportional to the total z-field ($B_z^{tot} = L_z + B_z$) sensed by the atoms. Also, the modulated signal $P_x^e(f)$ can be zeroed by adjusting the variable B_z, which provides a method to measure the light shift in the magnetometer. The light shift as a function of the pump beam intensity in the Cs magnetometer is shown in Fig. 3. The first pump beam with an intensity of 3.2 ∼ 16.2 mW/cm^2 results in a light shift of 1.0 ∼ 5.0 nT. The fitting curve based on Eq. (3) gives a slope of 0.31 nT/(mW/cm^2). For these data, as well as the data in Figs. 4 and 5, the second pump beam is switched off. Note that the SERF magnetometer shows a fT-level sensitivity, approximately 6 orders of magnitude below the light shift [27, 28].

To investigate the cross-talk effect induced by the light shift, z-component of the fields is fixed at B_z^0. The differential magnetic responses between $B'_{x/y} = +1.4$ nT and

$B''_{x/y} = -1.4$ nT as a function of the pump beam intensity have been illustrated in Fig. 4. Compared to the strong response to B_y, a slight response to B_x is observed due to the weak light shift when the pump intensity is less than 2 mW/cm^2. With the increment of light intensities, the response to B_y increase dramatically first and then decreases slowly, while a significant B_x response arises at higher intensities due to the intensity-dependent L_z in Eq. (2). The cross-talk effect, defined as the ratio of B_x response to B_y response in Fig. 4, is presented in Fig. 5. The cross-talk effect is about 31% when the B_y response is maximized, and it increases up to 50% at even higher intensities. Obviously, such a severe cross-talk effect can not be tolerated in practical applications. A similar phenomenon has also been observed in the comagnetometer based on K-Rb-^{21}Ne [16].

According to Eq. (2), the elimination of B_x response can be used as an evidence that the light shift has been zeroed. To validate the light-shift cancellation scheme proposed here, the magnetic responses to changes in B_x and B_y under different pump schemes with a selected beam intensity are recorded. The intensity of first pump beam is set to 8.0 mW/cm^2, which corresponds to a light shift of 2.4 nT in Fig. 3, and the second pump beam has an intensity of 6.4 mW/cm^2. The magnetometer responses to B_x and B_y with different pump schemes are shown in Figs. 6 and 7. In Fig. 6, the B_x response with the first pump beam is opposite to that with the second pump beam, implying that the light shift arising from the first pump beam is also opposite to that created by the second pump beam. This is consistent with the theoretical simulation displayed in Fig. 1. It should be addressed that the response to B_x is dramatically suppressed when both the first and second pump beams are switched on. According to Eq. (2), the suppression of B_x response indicates the light shift L_z has been zeroed in the scheme of two pump beams. For the B_y response depicted in Fig. 7, two individual beams lead to a response with the same sign. Unlike the cancellation of B_x response, the response to B_y under the illumination of two pump beams has been kept. Compared to the B_y response with a single pump beam, the response with counter-propagating pump beams is slightly greater due to the higher intensity summed up, which also agrees with the trends shown in Fig. 4. The two pump beams

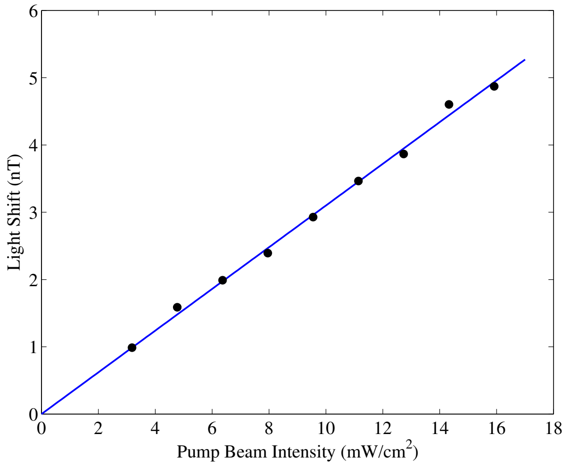

Fig. 3: Light shift as a function of the pump beam intensity. The longitudinal field B_z^0, which rejects the B_x response at the pump intensity of 0.5 mW/cm^2, is treated as the residual field along z direction in the magnetic shield. The total z-field is zeroed by the z-axis coil at each intensity, and the changes of applied field along z direction acts as the light shift arising from the first pump beam according to Eq. (5). The fitting curve (blue line) based on Eq. (3) gives a slope of 0.31 nT/(mW/cm^2). For these data, as well as the data in Figs. 4 and 5, the second pump beam is switched off.

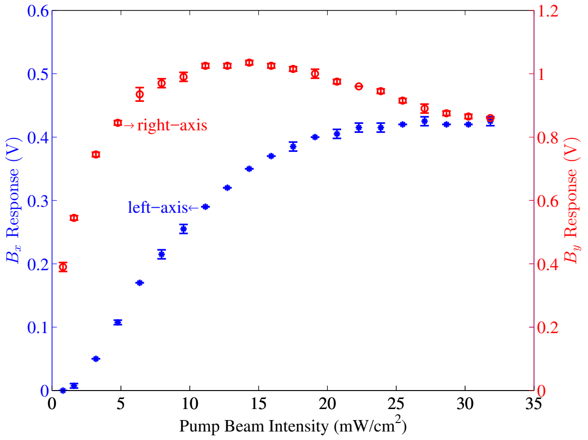

Fig. 4: The differential magnetic responses between $B'_{x/y} = +1.4$ nT and $B''_{x/y} = -1.4$ nT as a function of the pump beam intensity. The differential response to B_x, given by $\Delta P_x^e(B_x) = P_x^e(B'_x) - P_x^e(B''_x)$, is plotted against the left axis (blue dots), while the response to B_y, given by $\Delta P_x^e(B_y) = P_x^e(B'_y) - P_x^e(B''_y)$, is plotted against the right axis (red open circles). Each data set is measured twice, and the corresponding error bars are also shown.

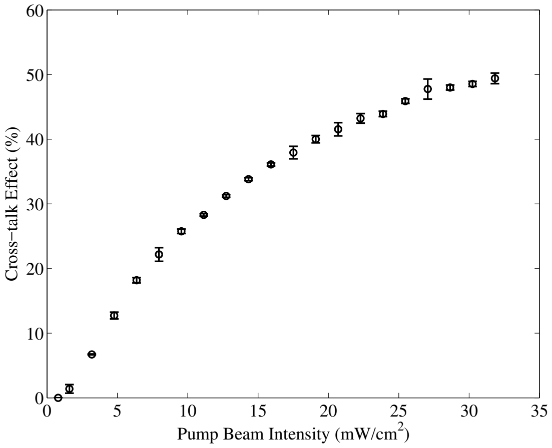

Fig. 5: The cross-talk effect as a function of the pump beam intensity. The cross-talk effect is defined as the ratio of $\Delta P_x^e(B_x)$ to $\Delta P_x^e(B_y)$ illustrated in Fig. 4.

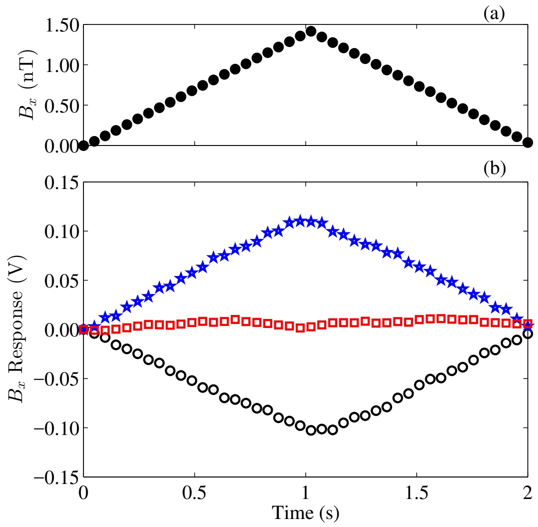

Fig. 6: Magnetometer response to B_x with different pump schemes. The top figure shows the input of the Cs magnetometer, while the bottom figure presents the magnetometer responses with different pump schemes. Under the illumination of the first (second) pump beam, the B_x response is indicated by the blank circles (blue stars). The red rectangles mark the response when both the first and second pump beams are turned on.

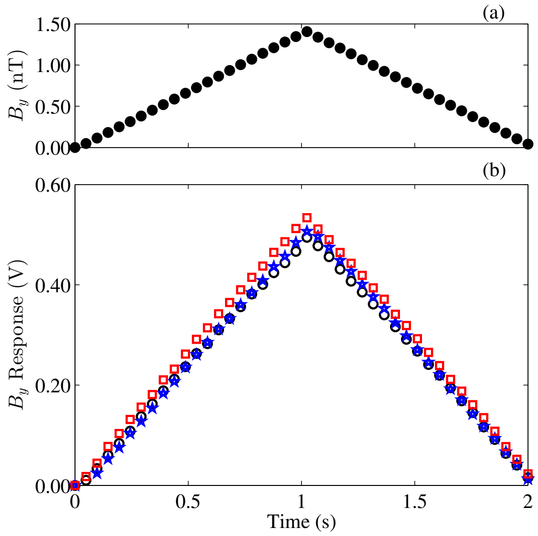

Fig. 7: Magnetometer response to B_y with different pump schemes. The top figure shows the input of the Cs magnetometer, while the bottom figure presents the magnetometer responses with different pump schemes. Under the illumination of the first (second) pump beam, the B_y response is indicated by the blank circles (blue stars). The red rectangles mark the response when both the first and second pump beams are turned on.

just act as one merged beam, whose intensity is approximately equal to the sum of the two lights, to polarize the atoms along z direction. According to Eq. (3), the beam intensity of the second pump beam required to cancel the light shift depends on the light frequency. By adjusting the laser frequency of the second pump beam, the required laser intensity, as well as the response to B_y, will also be changed.

Conclusion and Future Work. – In conclusion, here we have reported the light shift and the corresponding cross-talk effect in a SERF magnetometer based on Cs. And a pump scheme consists of two light beams has been proposed in order to avoid the cross-talk effect due to the light shift in atomic magnetometer or comagnetometer. By employing an additional laser beam with an appropriate polarization, intensity and frequency, we have demonstrated that the light shift in the optical pumping system can be effectively cancelled without degrading the atomic spin polarization [26]. The feasibility of the scheme has been validated in a Cs magnetometer, and the experimental results reproduce the expected behavior. From our perspective, the approach presented here provides a powerful tool to cancel the light shift in optical pumping systems, especially the hybrid optical pumping systems based on high-pressure vapor cell. Additionally, the cancellation of the light shift can be beneficial for a lower noise led by this fictitious field. And the adoption of counter-propagating pump beams can also assist in achieving a much more homogeneous polarization throughout the cell [29].

* * *

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