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Suppression of light-field shift of CPT resonances in optically dense media

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ABSTRACT

Presented for the first time are studies of the effect of optical medium density on the possibility of suppression of light field shift of a coherent population trapping (CPT) resonance excited with multi-component radiation generated by modulation of the injection current of a pumping single-frequency diode laser. It is shown experimentally and theoretically that the possibility of suppressing CPT resonance light shift depends on the optical density of the medium.

Keywords: coherent population trapping, light shift, atomic clock, rubidium, optical dense

1. INTRODUCTION

The existence of light field shift of coherent population trapping[1] (CPT) resonances is one of the major factors limiting accuracy of devices relying on the CPT effect (atomic clocks[2], magnetometers[3], etc.). Conventionally, resonance light shifts in compact CPT-based devices are minimized by choosing such modulation depth of the laser diode injection current that the resonance shifts from the radiation components are mutually cancelled[4]. The optimised depth of this modulation leads to an order of magnitude improvement[4] in long-term stability of atomic frequency references. Additionally, active methods of light shift suppression were proposed[5,6], which are based on continuous adjustment of the laser intensity modulation during the device operation. On the other hand, it was earlier demonstrated that it is not always possible to choose modulation depth so as to eliminate the CPT resonance light shift completely[7]. Usually, this was attributed to peculiarities of the spectral distribution of the specific laser device used. The conditions and the very possibility of light shift compensation may be also affected by other parameters. For example, it was demonstrated earlier that the buffer gas pressure affects the position of the point of light shift cancellation[8].

The present work studies other possibilities of light shift compensation in atomic clocks based upon coherent population trapping resonances. The effect of optical density of alkali metal vapour on the spectrum of radiation passing through is discussed. A possibility is identified of light shift elimination at a certain density of ^{87}Rb vapour. It is further shown that the optimal modulation depth at which the field shift may be eliminated becomes shallower at higher medium densities.

2. MODEL

In the present work, the CPT resonance is excited in ^{87}Rb atoms. The injection current of the laser diode is modulated at the half-frequency of the hyperfine splitting of the ground sub-levels $\omega_M = \omega_{hfs}/2 = 3.417$ GHz. Figure 1 shows what happens to laser radiation when it passes through a cell with rubidium atoms. The side components of the laser radiation spectrum of the first and zeroth order create a positive light shift while all the other components, a negative one[7]. When travelling across the optical cell, only resonant components of the radiation are absorbed, the intensity of non-resonant components remaining unaffected. Hence, in each transverse cross-section, atoms are exposed to radiation with different spectrum and the CPT resonance undergoes different light shift. The net light field shift of the resonance detected in the transmitted radiation depends then upon the optical medium absorbance, which, in its turn, depends on the optical cell temperature.

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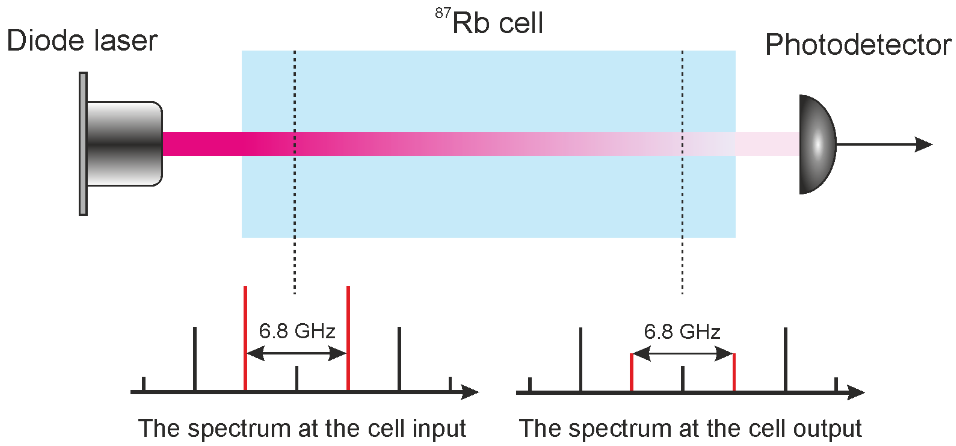

Figure 1. Evolution of the laser radiation spectrum during its passing through the optical cell with ^{87}Rb vapour.

For modelling of the light field shift, we used the model of Ref. 4. Electromagnetic radiation for excitation of the CPT resonance is created by modulation of the VCSEL injection current. This radiation may be presented as:

$$\mathcal{E} = \mathcal{E}_0 \sum_{n=-\infty}^{\infty} J_n(a) \cdot \exp[-i(\omega_0 \pm n\omega_M)t], \tag{1}$$

where $J_n(a)$ – Bessel function of order n, a – modulation depth, ω_M – RF modulation frequency, ω_0 – central frequency. The field shift between the ground and excited states is then as follows:

$$S = \frac{1}{4}\frac{\Omega^2 \Delta}{\Delta^2 + \Gamma^2/4}, \tag{2}$$

where $\Omega = \vec{\mathrm{d}} \cdot \vec{\mathcal{E}}/\hbar$ – Rabi frequency, Δ – detuning from the absorption line, Γ – decay rate ($\Gamma = 2\pi \cdot 5.746(8)$ MHz for the D_1 absorption line in ^{87}Rb atoms). Since we modulate the laser current at half the frequency of the hyperfine splitting of the ground sub-levels, the detuning for the transition F = 2 → F' = 2 equals $\Delta_1 = \omega_{RF} * (n-1)$, while for the transition F = 1 → F' = 2 it is $\Delta_2 = \omega_{RF} * (n+1)$. The total light field shift will be then the difference between the shifts of the two transitions $S = S_2 - S_1$. From the foregoing expressions we obtain that the total light field shift is proportional to the following:

$$S \sim \sum_{n=-\infty}^{\infty} \frac{J_n^2 \, \Delta_2}{\Delta_2^2 + \Gamma^2/4} - \frac{J_n^2 \, \Delta_1}{\Delta_1^2 + \Gamma^2/4} \tag{3}$$

It may be seen from Eq. (3) that each component of the laser radiation makes a contribution proportional to its amplitude. As they travel across the optical cell with rubidium atoms, the resonant components (±1) are absorbed and, therefore, make a reduced contribution to the overall light field shift. In order to take this effect into account, the amplitudes of the ±1 components were multiplied by a suppression factor β. Fig. 2 below presents the dependence of the light shift upon the modulation depth at varying suppression factors β. The curves show that the position of the point where the light shift is eliminated (indicated with a green dot) drifts toward shallower modulation as the amplitudes of the ±1 component decrease. This fact may be explained by stronger attenuation of the resonant radiation components at higher temperatures of the optical cell (and, correspondingly, higher medium absorbance), which results in smaller positive shift of the CPT resonance. For compensation of this effect, it is necessary to reduce energy in spectral side bands by reducing the modulation depth.

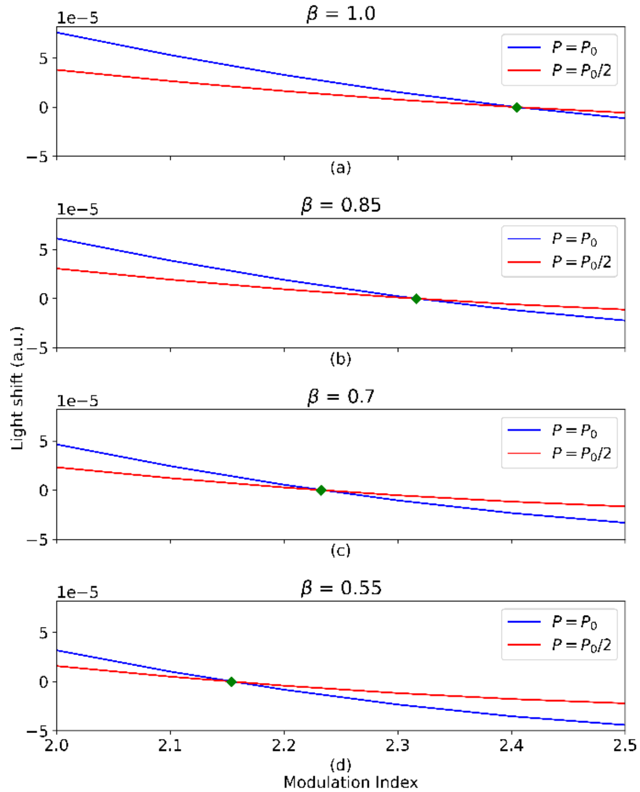

Figure 2. Dependence of light shift upon the modulation depth at different suppression factors β of ±1 sidebands of laser radiation: a) β = 1, b) β = 0.85, c) β = 0.7, d) β = 0.55.

3. EXPERIMENT

3.1 Experimental setup

The experimental installation is shown in Fig. 3. Its optical part included a VCSEL (Oclaro, 795 nm) emitting at the D_1 absorption line of ^{87}Rb, whose radiation was collimated and acquired circular polarisation passing through a quarter-wave plate. Further on, this radiation travelled across a cylindrical optical cell with a length of 5 mm and diameter of 4 mm filled with rubidium atoms[9]. The cell was placed inside Helmholtz coils that created a magnetic field parallel to the laser beam. Both the cell and the coils were enclosed into a three-layer magnetic shield made of μ metal. The radiation passing through the cell was measured with a photo-detector (PD). The optical layout also included a polarisation cube (not shown), which was used as an attenuator in order to adjust the laser radiation intensity. The laser injection current was modulated at half the frequency of hyperfine splitting of the rubidium ground level ($\nu_{RF} = \nu_{hfs}/2$ = 3.417 GHz) in order to create side-bands. Therefore, the CPT resonance was excited by the ± 1 components of the side-bands of the laser radiation. The resonance was scanned by a 2-kHz modulation, its parameters being optimal[10]. This signal was used as the input to a lock-in amplifier that adjusted the frequency of a local oscillator, which, in turn, was used as the reference signal for a frequency synthesizer. The experimental configuration also includes another lock-in amplifier for stabilisation of the laser wavelength using sine-wave signal at 10.1 kHz (this frequency was selected so as not to be multiple of other modulation frequencies).

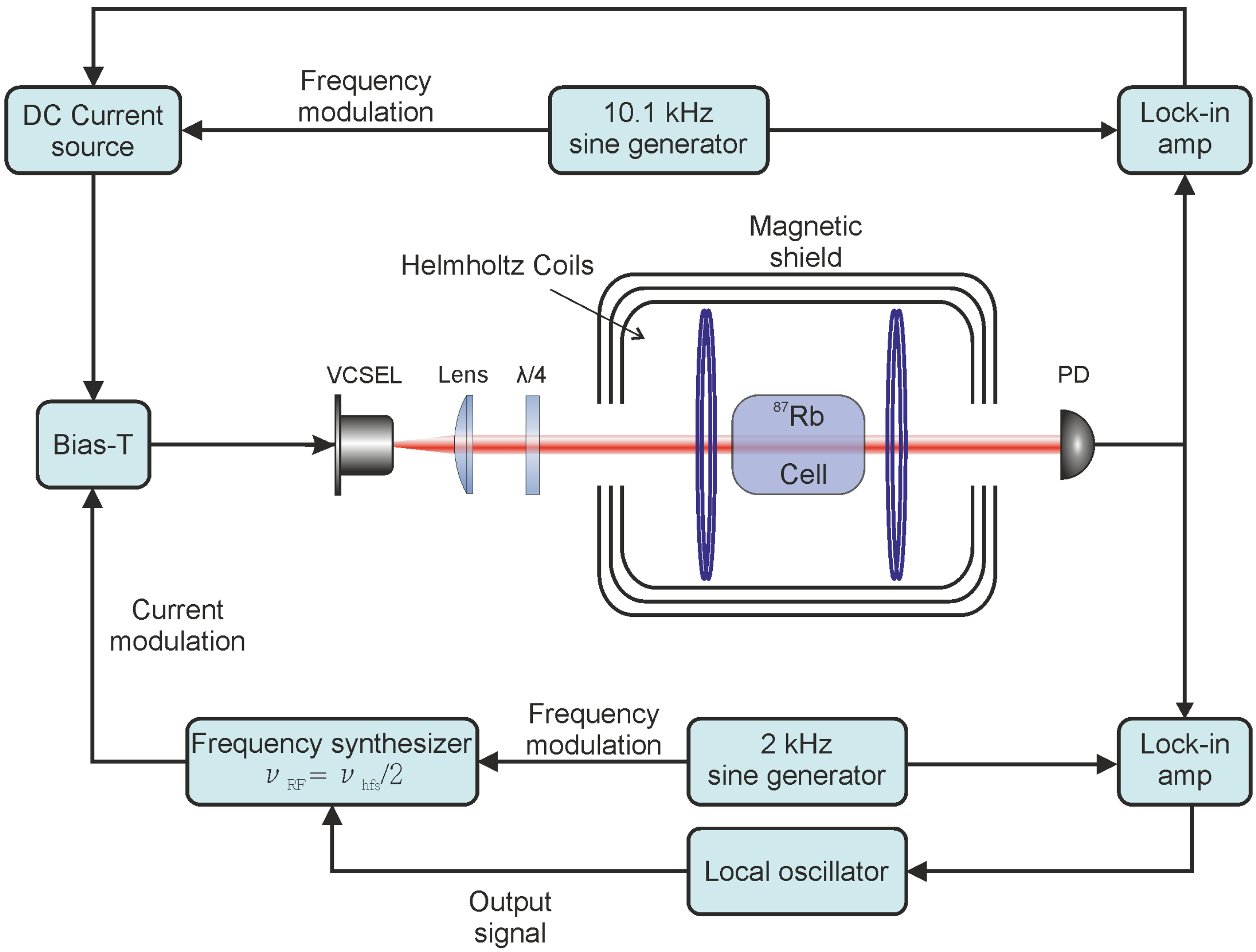

Figure 3. Experimental scheme.

3.2 Results and discussion

With the laser emitting single-frequency radiation at 20 µW, we measured the absorption of the relevant atomic transitions (F = 1 → F' = 2 and F = 2→ F' = 2) as dependent on the cell temperature. This absorption was defined as the ratio of the exit amplitude at the transition frequency with the heated cell to that with the cold cell. As it is shown in Fig. 4, higher temperatures result in relatively high absorption of laser radiation. At the cell temperature of 80 °C, laser radiation absorption grew to approximately 25 % and 30 % for different transitions.

Practically, we do not know the relation between the modulation depth a (Eq. (1)) and the power of the RF signal modulation. Also, the atomic clock frequency may only be measured relatively. In spite of this, we can compare theory and experiment qualitatively. In order to find the modulation power at which the light shift is eliminated, the atomic clock frequency was measured at laser radiation input of 10 µW and 20 µW at different powers of RF radiation (Fig. 4). If the frequency of the atomic clock does not depend on the radiation power at a certain modulation power, then this particular value of the modulation power is the point of light shift elimination. This measurement was performed at cell temperatures of 55 °C, 65 °C, 75 °C, and 85 °C.

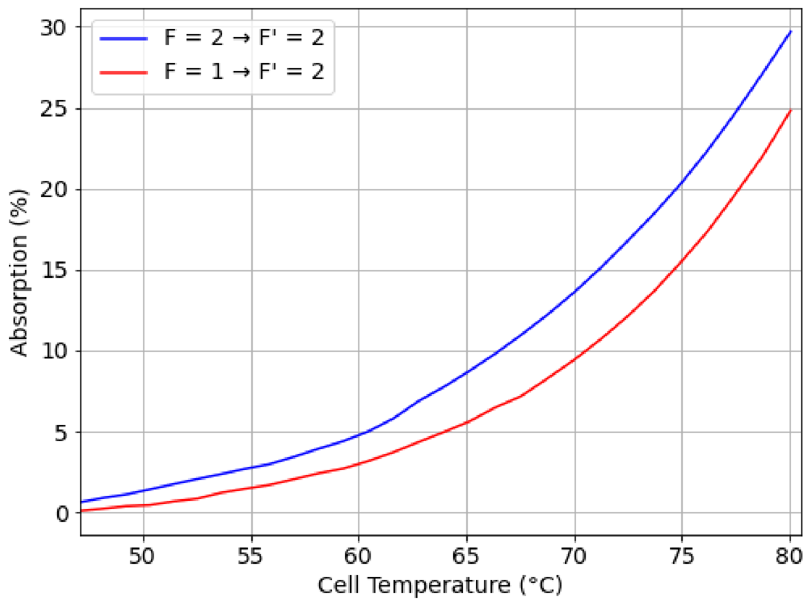

Figure 4. Absorption coefficient.

The results demonstrate that at low temperature these curves do not intersect and, therefore, the light shift is not eliminated (Fig. 5 a, b). This is because, most probably, the zero-shift point is beyond the measurement range. Greater modulation power was not possible because the signal/noise ratio approached 1. At higher temperatures, there are zero-shift points. At the cell temperature T = 75 °C, the field shift is cancelled at the modulation power equal to 0.6 dBm and 3.5 dBm, while at T = 85°C, it was cancelled at 0.5 dBm and 3.1 dBm. Thus, as the cell temperature rises, the modulation power, at which the light shift may be eliminated is reduced. This happens because higher cell temperature increases absorption (Fig. 3). Hence, the ±1 side-bands of the laser radiation are also stronger absorbed. These components contribute then less to the light shift and so the zero-shift point moves. It can also be seen from the graphs that at higher temperatures there appears a second point of light field shift suppression (Fig. 5 c, d). This does not in itself contradict the theory, but the interesting point is that resonant frequencies in these points differ, even though they should coincide according to Eq. (3). This circumstance may be explained by the fact that as RF modulation power rises, so does the contribution of amplitude modulation, which leads to asymmetry of the laser radiation spectrum[11], which gives rise in the end to a noncompensible resonance shift.

4. CONCLUSION

The present work studies the effect of optical absorption of alkali atoms upon the possibility of light shift elimination. The presented theory demonstrates that the stronger are absorbed the resonant components of the laser radiation, the shallower modulation is necessary for elimination of the light field shift. This theoretical result was also confirmed in experiment. It has been additionally shown that relatively low absorbance of the alkali atoms makes light shift compensation of the CPT resonance impossible.

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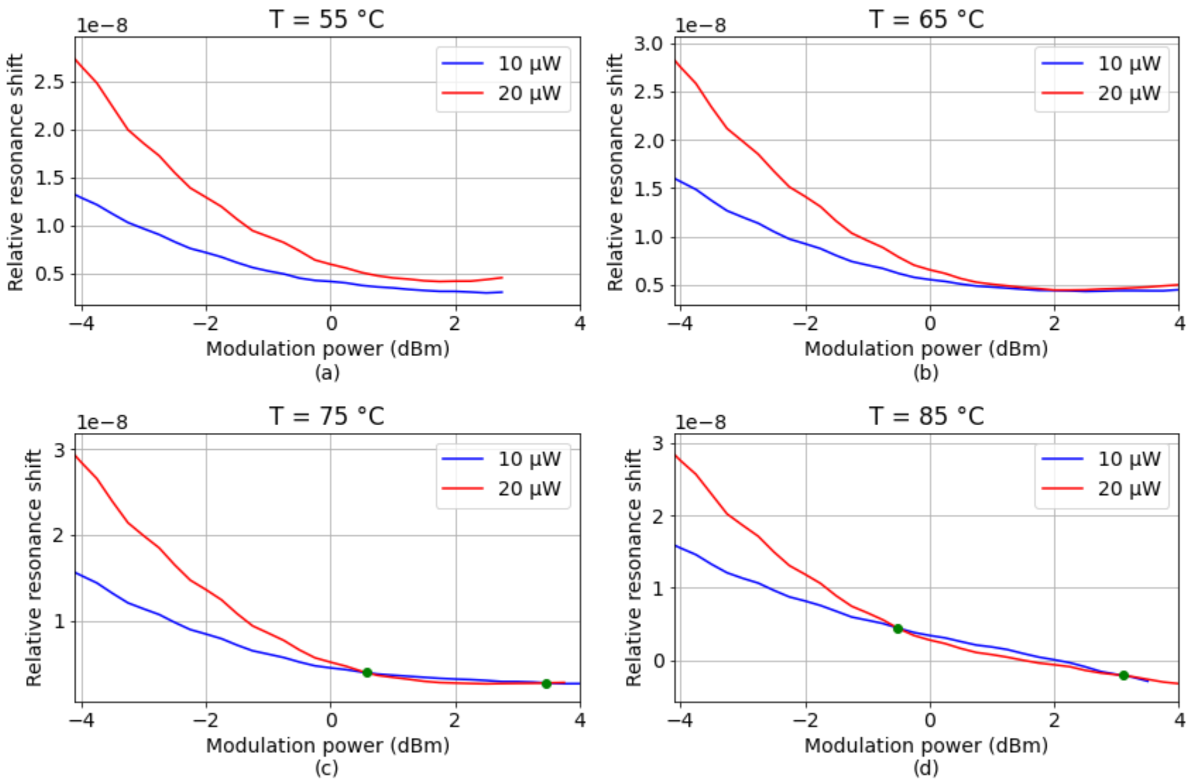

Figure 5. Dependence of the atomic clock frequency upon the modulation power. Blue curve corresponds to the radiation power of 10 μW, and the red curve, to 20 μW. The cell temperature was (a) 55 °C, (b) 65 °C, (c) 75 °C, (d) 85 °C. Green dots indicate curve intersections.

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