# Suppression of light shifts in pulsed CPT atomic clock using combined error signal in Ramsey spectroscopy

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## ABSTRACT

This study details the experimental use of a combined error signal (CES) method in Ramsey spectroscopy with a pulsed Rb CPT atomic clock to counteract light shift frequencies. By employing a linear combination of two error signals, generated during different free evolution times in a pulse sequence, this method effectively neutralizes field shift impacts. The precise calibration of coefficient allows for an error signal that remains constant despite varying field shifts. Experimentally, this technique has proven to reduce the effects of fluctuations in optical radiation and modulating microwave signal power, which can significantly enhance the long-term stability of atomic frequency standards.

**Keywords:** CPT atomic clock, rubidium atomic clock, Ramsey spectroscopy, light shift cancellation

## 1. INTRODUCTION

Atomic frequency standards relying on coherent atomic transitions play a key role in today's metrology, providing highly precise measurements of frequency and time[1–3]. One of the fundamental problems limiting the accuracy of such standards is the presence of light field shifts caused by interaction of atoms with the electromagnetic field of the probe laser[4–8]. These shifts may result in considerable skewing of frequency parameters of an atomic transition, which leads to systematic errors. This is why a great deal of attention has been recently drawn to development of new approaches in spectroscopy that could reduce or completely eliminate the influence of laser radiation intensity fluctuations upon the frequency of the reference resonance[9–11].

Earlier on, it was possible to develop an approach for suppression of light shift and improve significantly metrological parameters of atomic clocks relying on coherent population trapping (CPT) with the continuous measurement technique[12,13]. This approach, based on the phase hopping method[14] and generation of auxiliary error signal for stabilisation of the UHF modulation power around the point where the light field shift is eliminated[15–17], has led to substantial reduction of the light shift effect on measurement accuracy, thus opening new potential for higher stability and reliability of atomic standards.

This work focuses on experimental implementation of the method for suppression of light field shifts in the pulsed CPT resonance excitation technique. Theoretical foundations of this method were presented earlier in[18]. The principle of this approach consists in generation of two error signals following the phase hopping method that correspond to different durations of free evolution of atoms. Since the light shift depends on the duration of the 'dark time', these two error signals contain different information about the light shift amount. This, in turn, makes it possible to synthesise a new error signal as a combination of the two original ones, which is independent of the field shift.

Therefore, application of a pulsed sequence with two durations of free evolution allows compensation of light shift influence and significant improvement of measurement precision. Experimental results generated in the course of this work demonstrate the effectiveness of the proposed method and its potential in atomic frequency standards, thus opening up new opportunities for development of more precise and stable frequency and time references.

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## 2. EXPERIMENTAL SETUP

The experimental layout is shown in Fig. 1. The laser radiation source was a semiconductor DBR laser with a fibre output emitting at 794.7 nm. Its output is delivered by fibre to a phase modulator. The phase modulation frequency was set to half the hyperfine splitting frequency of the ground state of rubidium-87. Using an external phase modulator eliminates spectrum asymmetry problems that arise, for example, with direct current modulation in a VCSEL[19–22]. Thereupon, the radiation is guided (also by fibre) through a collimator into an optical isolator for elimination of any possible back reflection. The electro-optical amplitude modulator following it, along with the first detector and a beam splitter forms the power control and stabilisation loop. The polarisation cube inserted after the amplitude modulator serves for primary power adjustment. Part of this radiation passing through the beam splitter enters the acousto-optical modulator that was used to form pulse trains by amplitude modulation of the input RF signal. A half-wave plate positioned behind is used for secondary power adjustment. The polarising cube following it sets a linear polarisation at the angle of $\pi/4$ with respect to the axis of the quarter-wave plate. Therefore, the 5-mm long optical cell with buffer gas[23] is entered by circularly polarised resonant radiation. The optical cell itself is placed between two Helmholtz coils inside a three-layer magnetic shield. The photo-detector placed after the optical cell was used to monitor the intensity of the exiting radiation. The signal from this detector was used for generation of the error signal for frequency stabilisation of a quartz oscillator serving as the reference for a phase synthesiser that forms an UHF (3.4 GHz) signal for the phase modulator. Signal digitization and error signal synthesis were performed using a modular PXI system from National Instruments. For stability measurements, an additional rubidium atomic frequency reference and a frequency comparator were used.

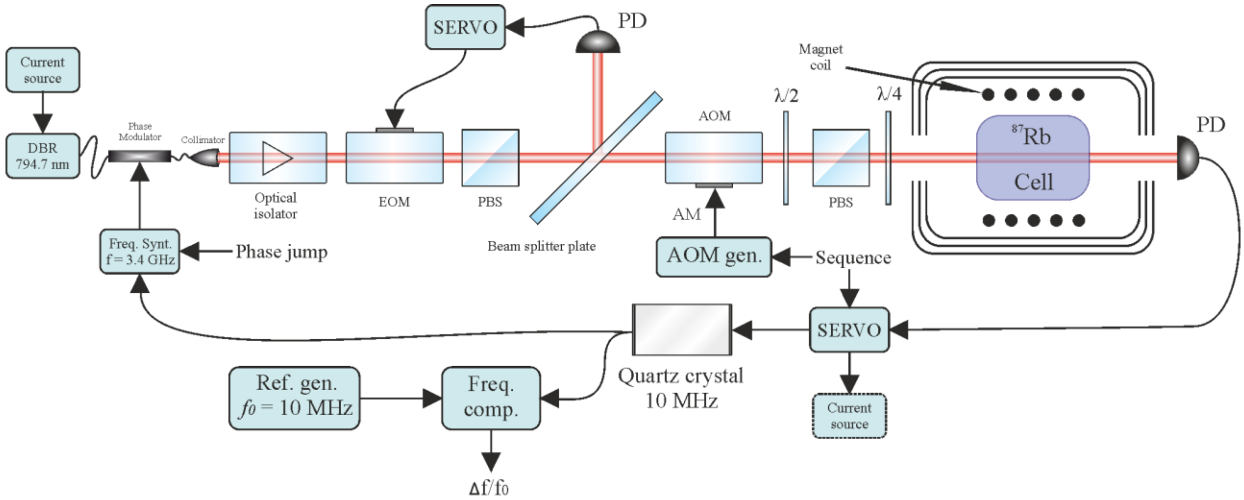

Figure 1. Diagram of the experimental installation. AOM – acousto-optical modulator, VCSEL – vertical-cavity surface-emitting laser, PD – photodetector.

## 3. RESULTS

Fig. 2 demonstrates the pulse sequence used in our experiment for frequency stabilisation via the combined error signal. The pulses sent after free evolution time $t_1$ produce the first error signal SE($t_1$). The pulses following after free evolution time t2 are the basis of the second error signal SE($t_2$). In order to provide alternation of pulses with opposite phase hopping in each of the error signals, we used a modified phase hopping sequence. The combined error signal SE is a linear combination of the initial error signals: $SE_k = SE(t_1) - k \cdot SE(t_2)$. The typical shape of error signals is given in Fig. 3. It should be mentioned that the minimal pulse duration is not determined by the rate of optical pumping into the CPT state (as it is in a Λ-system), but rather by the life time of the trap state (the last Zeeman sub-level), which has no dependence on the field intensity. This is why the pulses should be long independently of the radiation intensity, in order to pump atoms into the equilibrium state. At insufficient pulse duration, the atomic state will depend on the dark time preceding the pumping pulse, thus resulting in a residual field shift in the error signal.

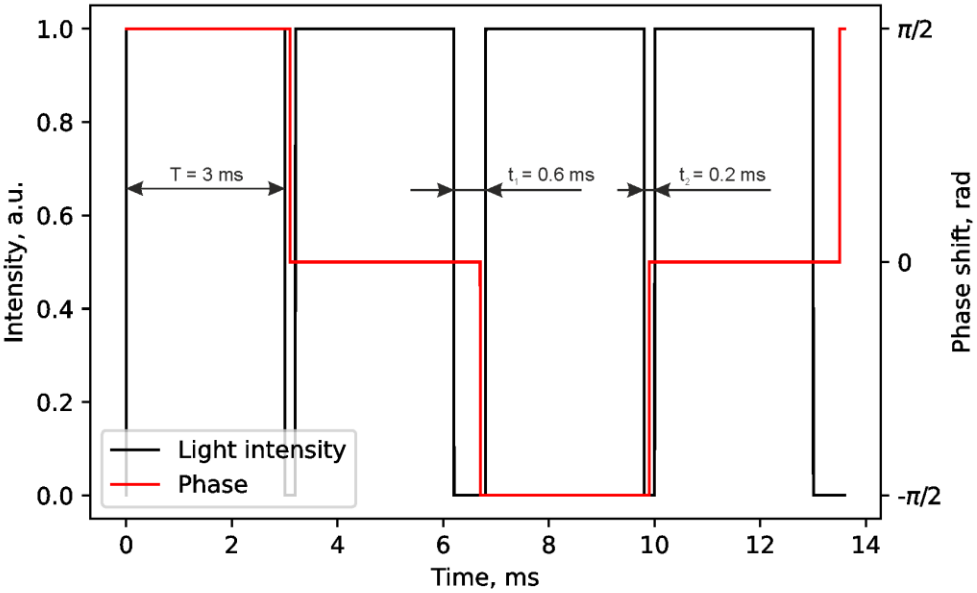

Figure 2. Fragment of a periodical pulse sequence for generation of the combined error signal.

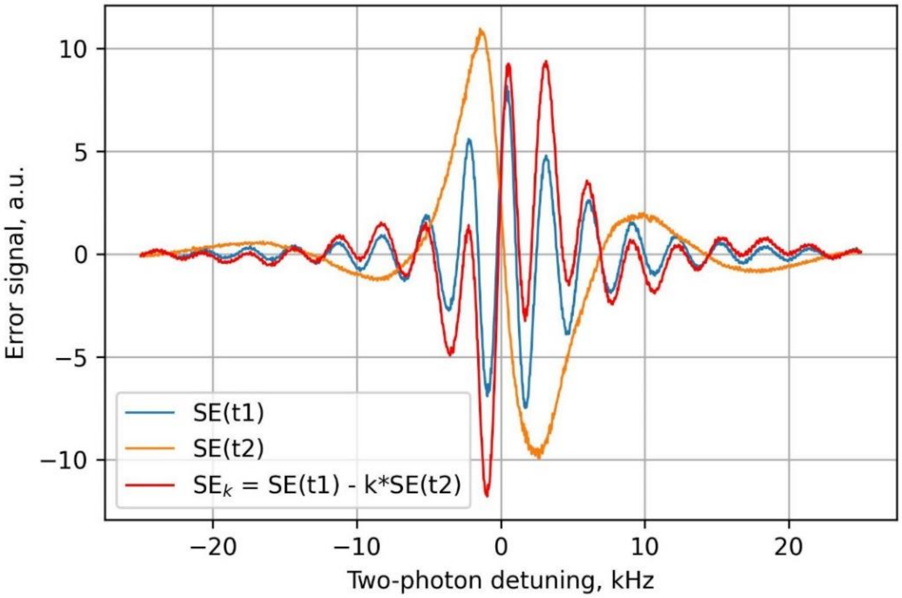

Figure 3. Typical shape of the measured error signals.

According to the theory, calibration coefficient k depends upon the product of the CPT state relaxation rate and the difference of free evolution durations. Fig. 4 presents the dependence of the frequency shift at different radiation power and the depth of UHF modulation upon the value of coefficient k. This plot shows that at k ~ 0.51, the frequency does not depend on the radiation power and modulation depth, which corresponds to the desired calibration coefficient value.

Therefore, it has been experimentally demonstrated that application of a combined error signal may eliminate the influence of power fluctuations of the optical radiation and UHF modulation signal upon the position of the error signal. This, in its turn, should significantly improve the long-term stability of CPT atomic clocks.

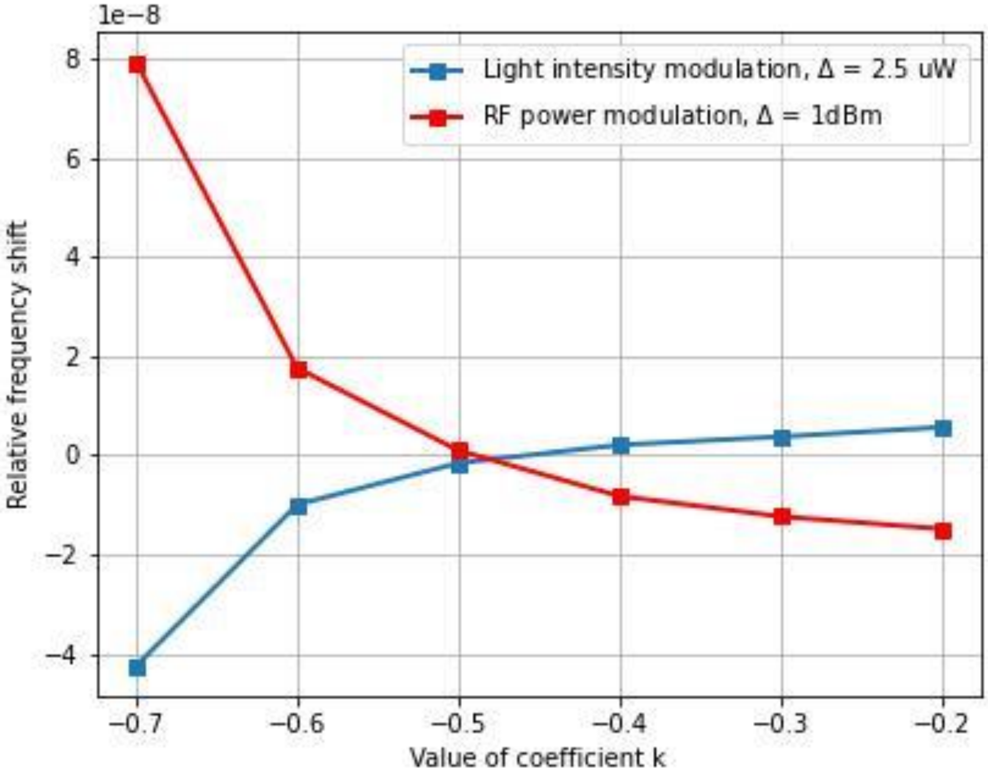

Figure 4. Dependence of the resonant frequency shift upon the calibration coefficient in the combined error signal at different levels of pump radiation power and the UHF modulation depth.

## 4. CONCLUSION

In this work, a method of generalised Ramsay spectroscopy of CPT resonances was implemented on the basis of an atom interrogation sequence at two different durations of free evolution. According to the earlier developed theory of combined error signal in the auto-balanced method of Ramsay spectroscopy, algorithms were developed and tested for generation of error signals and frequency stabilisation in atomic clocks. For a combined error signal, a value of the calibration coefficient was found, at which the zero position of the error signal is not sensitive to fluctuations of the optical radiation power and the power of modulation UHF signal. Therefore, high efficiency of light field suppression has been experimentally demonstrated that should eventually lead to significant improvement of long term stability.

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