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Investigation of interaction of THz radiation with blood components for diabetes mellitus diagnostics

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Diabetes mellitus is a group of metabolic diseases characterized by hyperglycemia resulting from defects in insulin secretion, insulin action, or both [1]. There is a direct relationship between the level of glucose in the blood of patients with diabetes and the probability of developing complications of the disease [2]. Accurate and efficient assessment of blood glucose concentration is critical in clinical management of many pathological conditions in human population.

One of the most important benefits of terahertz spectroscopy methods is the possibility of non-invasive analysis of biological samples [3]. Transmission mode of spectroscopy is common way for collecting data about easy extractable media. On the one hand transmission mode of medium analysis provides accurate results, but can be unsuitable for completely non-invasive investigation of biological tissues and fluids [4,5]. On the other hand, reflection mode of spectroscopy cannot be used for direct blood optical measurement due to the location of blood below the surface of the human body. Moreover, THz reflected signal considerably weakened due to the water contained in the skin layer. Despite this, capillary blood located in fingers’ nail beds may be investigated through the nails in the reflection mode.

In this paper we present the results of THz spectra measurements of nails and whole blood samples with different glucose concentration. Our THz spectrometer had been described previously [4,5]. We investigated the frequency dispersions of complex refractive index ($\eta_{\text{real}}$ and $\eta_{\text{imag}}$), absorption coefficient ($\alpha$), penetration depth ($L$) complex permittivity ($\epsilon_{\text{real}}$ and $\epsilon_{\text{imag}}$) in the frequency range of 0.2 to 2.0THz. Analysis of the experimental spectra was performed by comparing spectra of biological samples with a Debye model of the dielectric function of water.

Observed results highlight the prospective of the described technique use for medical diagnosis of diabetes.

References
Pulsed optical pumping technique in application to rubidium compact atomic clocks

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Currently, a vital need exists for the compact (a mass of ~10 kg and a volume of ~10 l) quantum frequency standards (QFS’s) possessing a short-term instability better than $5 \times 10^{-13}$ (the averaging time 1 s) and a long-term instability at a level of $10^{-15}$ (the averaging time $10^5$ s).

Such QFS’s can be applied in radio navigation systems, as well as for synchronization of telecommunication networks and local time scales, including on-board ones. However, the existing microwave QFS’s (including atomic beam tubes with magnetic selection of quantum states, atomic beam tubes with laser pumping, fountain-type clocks based on cold atoms, hydrogen frequency standards of active type, passive hydrogen frequency standards, and rubidium vapor cell frequency standards with lamp optical pumping) do not satisfy modern requirements to on-board QFS’s for rapidly progressing global navigation satellite systems by at least some of such parameters as instability, mass and overall dimensions, energy consumption, reliability of operation.

The compact atomic clocks based on Rb gas cell with pulsed optical pumping and detection and with Ramsey interrogation in microwave cavity demonstrate improved frequency stability compared to that of existing lump-pumped Rb frequency standards and have the capacity to reach the stability level of the passive hydrogen masers [1-4]. The main physical advantage of the POP clocks is that the atomic clock transition is probed at the absence of optical radiation in the cell. This leads to the essential suppression of the light shift (ac Stark shift) which is the main source of frequency instability in optically pumped microwave frequency standards.

In the presented work we report the performance of the pulsed optically pumped Rb clock laboratory prototype. The Ramsey fringes with linewidth of 185 Hz, with no averaging on cycles at microwave frequency sweeping around clock transition frequency were obtained (Fig. 1). The study of the central fringe contrast in dependence on the pumping and detection laser pulses duration and intensity as well as on the cell temperature was conducted. The optimized central fringe contrast value exceeding 40% at cell temperature of 65 °C has been reached. We also report the achievement of the Rabi-Ramsey CPT resonances in lin||lin configuration of bichromatic laser radiation [5] in the same cell (Fig. 2). The magnetic sensitivity of the Rabi – Ramsey CPT transitions is studied. The perspectives of building atomic clock based on CPT will be discussed.

Fig. 1 Ramsey fringes with central fringe contrast over 40% achieved by implementing POP technique.
Fig. 2 Ramsey- CPT line without averaging on cycles.

References
The researching of the structure of the laser plasma by methods of spectral diagnostics of ion luminescence

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The processes occurring in the ionosphere and magnetosphere of the Earth are difficult to model ([1]). So the creation of physical models describing the interaction of space plasma with external disturbances is impossible without an experimental testing in a laboratory.

In experiments made in the laboratory 3.1 of high-power laser energy (Department of laser plasma) ILP SD RAS, laser plasma is explored to imitate fast processes in the near-earth space environment. One of the important parameters is the speed of movement of various ion components of the laser plasma. Doppler broadening and shift of spectral lines are effects that allow to measure the speed. So, it is possible to measure the transverse velocity component and the cone of the laser plasma using a Doppler formula. In this work laser targets made of polyethylene were used to get hydrogen and carbon ions of different charges which have a different angle of a dispersion. The measurement of this effect is possible only by spectral methods with using of ccd-matrix for the registration of the shape of line.

Also, the study of changes of the intensity of spectral lines by the inclusion of different magnetic fields (Fig. 1) and varies the distance from the laser target (Fig. 2) was made in the presented work.

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Fig. 1 Spectral lines of hydrogen under the influence of the magnetic fields
Fig. 2 Carbon spectral lines at the different distances from the laser target

References
Harmonic generation by the relativistic plasma resonance

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It is common knowledge that a nonlinear transformation of an electromagnetic wave excited by a laser in an inhomogeneous plasma leads to a resonant enhancement of a potential electric field in the vicinity of a plasma critical density and the harmonic radiation in vacuum. The harmonic generation process of a low-intensity radiation propagating in an inhomogeneous plasma was investigated in [1] using perturbation theory. In that framework an exponential decrease in the harmonic amplitude with increase in the harmonic number was obtained. The authors of [2] went beyond the perturbation theory by taking into account the nonlinearity of electron motion, but neglecting the relativistic effects. By applying the renormalization group transformation approach, they calculated the amplitudes of harmonics of the electromagnetic wave incident on a nonuniform plasma. They also found that the intensity of harmonics decreases much more slowly with increasing harmonic number than it was predicted by the weakly nonlinear theory. An adequate generalization of the nonlinear theory of the harmonic generation at high laser intensities, when relativistic effects near the plasma resonance becomes essential, is still lacking.

In this study we present the harmonic generation theory by the relativistic plasma resonance mechanism in an inhomogeneous laser plasma. A stationary analytical solution of the nonlinear equations governing the spatiotemporal structure of the electromagnetic field and electron dynamics in the vicinity of the plasma resonance are calculated [3] via the renormgroup symmetries method. Application the formalism of renormalization group transformations to construct the solution allows us to take into account the nonlinearity of electron motion, including the relativistic effects. A nonlinear current, which is the source of the harmonic generation in vacuum and harmonic amplitudes, are found. Relativistic nonlinearity of the plasma wave leads to the phase modulation of the electron oscillations, which determines the smooth modulated spectra of the radiation field. Dependences of the harmonic generation efficiency on the laser radiation incidence angle and on the plasma inhomogeneity scale are presented. It is shown that with fixed pump field intensity the efficiency of the higher harmonic generation increases with increasing the plasma inhomogeneity scale. The applicability limits of the obtained theory, which are determined by the conditions of plasma wave breaking near the resonance, are established and analyzed in detail for typical laser and plasma parameters. Comparison with non-relativistic theory shows that the conclusions obtained in the weakly nonlinear [1] and nonlinear nonrelativistic [2] theories of the harmonic generation should be partially reviewed and corrected.

References

Formation of a luminescent layer in LiF crystals by the glow discharge radiation

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The formation of thin layers of luminescent defects on the faces of planar lithium fluoride crystals located in the positive column and the Faraday dark space of a glow gas discharge at the pressure of air 1-10 Torr was studied.

The objective of this work was to determine the types of formed color centers, to study the spectral and kinetic characteristics of their luminescence, and to disclose the mechanism of their formation and the character of glow discharge zones in which the formation of defects is most efficient.

Scanning confocal fluorescence microscope MicroTime 200 with picosecond time resolution with a spatially-selective time-correlated single photon counting was used to determine spectral-kinetic characteristics of photoluminescence of lithium fluoride irradiated samples. Spectra of photoluminescence measured under excitation by picosecond laser with a wavelength of 470 nm were recorded by the spectrometer Ocean Optics 6500.

Fig. 1. Luminescence spectra (a) and kinetics (b) of LiF crystals irradiated by VUV- radiation from a glow discharge: 1 and 3 – crystal placed in the positive column, 2 and 4 – in the Faraday dark space; 1 and 4 – for anodic side (side of crystal facing to the anode), 2 and 3 – for cathodic side.

It has been established that basically two types of color centers are formed on the surface layers of crystals (fig.1): F2 and F3+ color centers with luminescence bands peaking at ~ 680 and 530 nm, respectively. The defects were shown to be formed under the influence of vacuum ultraviolet (VUV) photons. The VUV radiation intensity distribution in the discharge gap was measured by the method of thermostimulated luminescence using the CaSO4 Mn thermoluminophor. The main source of this radiation was the anodic and cathodic voltage drop regions in a glow discharge. Therefore, the coloring of crystals near these regions is most effective. Glow discharge can be successfully used to form thin luminescent layers on the surface of transparent insulators for various scientific and practical applications.

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Features of defect formation in crystalline anisotropic media under the influence of coherent pairs of femtosecond laser pulses

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In this paper, we study the possibility of positioning the laser effect on the given internal regions of the crystalline medium in the formation of its luminescence centers by laser radiation. The combined effect of two components of a coherent pair of intense femtosecond laser pulses on a given region is considered.

In the case of high nonlinear processes of interaction between light and matter, many new phenomena arise. These phenomena complicate the overall picture of the interaction: self-focusing and multiple filamentation of laser radiation, supercontinuum generation, the appearance of electron-hole plasma. Defect formation occurs when there is a filamentation of the laser beam with a sharp increase in its intensity to values sufficient for interband ionization.

![Fig. 1. Structure of single luminescent traces induced in the central (1) and initial (2) regions of the channel.](image)

Self-focusing and filamentation require a certain distance. If it is greater than the value of \( Y = \frac{c\tau}{\Delta n} \) (\( c \) - speed of light, \( \tau \) - pulse duration, \( \Delta n \) - the value of birefringence of the medium), then we can not observe any spatial modulation of the concentration of the created luminescence centers. This assumption was confirmed in the first experiments (Fig. 1). The figure shows luminescent images of two luminescent traces from the color centers created by single filaments focused in the initial and central parts of the sample. In the initial part we observe modulation, in the Central part there is no longer.

In this work, direct experiments have studied the question of whether it is possible, by changing the magnitude of the shift between the components of coherent pairs of femtosecond pulses at the entrance to the crystal, to move the modulation picture of the concentration of the induced luminescence centers throughout the crystal, or, due to a significant degree of randomization of the interaction characteristic of the high-nonlinear interaction, it is impossible.

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Liquid crystals (LCs) represent a convenient medium for the development of adaptive optical materials and devices due to their distinct anisotropic properties and the strong sensitivity to external influences. LC-systems can be used as spatial light modulators, tunable light waveguides, phase plates, diffractive elements etc.

Spatially confined LCs possess a number of specific orientational structures caused by the competition between spatial and surface forces [1]. The variety of sophisticated structures is revealed for the cholesteric LC microdroplets [2] having supramolecular helical structure.

In the present study, the light-induced structure transformation of the cholesteric LC microdroplets in glycerol is considered. The basic idea is manipulation by the boundary conditions at the trans-cis photoisomerization of azobenzene polymer molecules adsorbed from the LC bulk onto the LC-glycerol interface [3].

The 5CB nematic host was doped with 0.1 wt % of chiral compound and 0.1 wt % of linear polymer with side-chain azobenzene fragments. The LC mixture was dispersed in the glycerol forming spherical droplets with the size from 1 to 100 μm. The light emitted diode (LED) with emission maximum at 400 nm was used to induce photoisomerization process of azobenzene moieties. The orientational structures were investigated with the help of polarized optical microscope in the bright field. The cholesteric LC droplets initially have degenerated planar boundary conditions with the glycerol. Under LED irradiation with light intensity \( I = 40 \text{ mW/cm}^2 \) during 30 min, the boundary conditions are changed from planar to homeotropic inducing the structure transformation of LC droplet. After irradiation, the structure typical to homeotropic anchoring (Fig. 1a,b) relaxes to the initial one (Fig. 1f). Here it is clearly shown the formation of point defects \( P \) and \( P' \), which finally coalesce forming the \( \chi \)-disclination (Fig. 1c-f).

The photoinduced structures of cholesteric LC droplets depend on the droplet size with respect to the cholesteric pitch, parameters of irradiation (light wavelength, intensity, exposure time). Here we considered one of the possible transitions.

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References
Geometric phase in non-standard settings

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Geometric (topological) phase \( \varphi_{geom}(C) \) is a characteristic attributed to any curve \( C \) in a complex projective space of quantum states, i.e. to any quantum state evolution of an isolated system [1,2]. It was first defined for Hamiltonian evolution of a pure quantum state [1]. The present work is dedicated to expanding this concept to a broader range of physical situations – mixed states of open quantum systems, and the state change incorporating pre- and post-selection procedures (also known as two-state vector formulation of quantum mechanics [3]). First, we derive a general expression for geometric phase of open quantum system as a function of its history – a series of measurement outcomes generated during a system passage through a chain of Mach-Zehnder interferometers, given the arbitrary input state. This is a further development of operational approach to geometric phase introduced in [4,5]. In [4] a geometric phase was defined as a purely kinematic concept, analogous to [2]. The necessary step towards defining geometric phase for open quantum system is made by replacing a unitary evolution in each interferometer by interaction with the element of environment followed by measurement of some environment observable.

The scheme under consideration is shown in Fig. 1. The entrance interferometer numbered with (0) introduces a controllable phase shift \( \theta \) to the state of spatial motion of the system, which is used for detecting geometric phase from the shift of interference pattern at the output of interferometer. All the interferometers to follow contain interaction with environment in a standard pre- or post-selection procedure (also known as two-state vector formulation of quantum mechanics [3]).

The change of the internal state during propagation through an interferometer can be described with the help of operators \( \hat{E}_{i_n}(0) = \langle e_{i_n}^{(n)} | e \rangle, \hat{E}_{i_n}(1) = \langle e_{i_n}^{(n)} | \tilde{U} | e \rangle \), where \( \hat{E}_{i_n}(0) \) describes the interaction if the system goes via horizontal arm (no interaction, only measurement), and \( \hat{E}_{i_n}(1) \) describes it if the system goes vertically (interaction followed by measurement). Here \( \{ | e_{i_n}^{(n)} \rangle \} \) is the basis of \( n \)-th observable’s eigenstates. The geometric phase is extracted from the difference of detection probabilities at the output \( D_\gamma = Tr \left[ \hat{\rho}_{11}^{(N+1)} - \hat{\rho}_{00}^{(N+1)} \right] \) and the final expression for it reads

\[
\theta_{geom}(I) = \arg Tr \left[ \sum_{\sigma=0,1} \left( \hat{E}_{\sigma}^+(\sigma, 1) - \hat{E}_{\sigma}^+(\sigma, 0) \right) \cdot \left( \hat{E}_{\sigma}^+(\bar{\sigma}, 1) + \hat{E}_{\sigma}^+(\bar{\sigma}, 0) \cdot \hat{\rho}^{(in)} \right) \right]
\] (1)

where \( \bar{0} = 1, \bar{1} = 0 \). The operators \( \hat{E}_{\sigma}^+(\sigma^{(N)}, \sigma^{(1)}) \) explicitly depend on the measurement record \( I \):

\[
\hat{E}_{\sigma}^+(\sigma^{(N)}, \sigma^{(1)}) = \sum_{\sigma^{(N-1)}=0,1} \cdots \sum_{\sigma^{(2)}=0,1} \hat{E}_{i_n}^{(1)}(\sigma^{(1)}) \cdots \hat{E}_{i_1}^{(1)}(\sigma^{(1)}) \cdot (-1)^{\sigma^{(N)}\sigma^{(N-1)} + \cdots + \sigma^{(2)}\sigma^{(1)}}
\] (2)

This is the central result of the present work.

The obtained expressions were applied to the case of two-dimensional system (a qubit) and the same environment, as an illustration. The interaction \( \tilde{U} \) was chosen from the class of controlled two-qubit operations. The values of the geometric phases corresponding to different measurement records were evaluated from (2) (see Fig. 1), and their certain features (particularly, inability to gain a non-trivial geometric phase for some input states and certain choices of \( \tilde{U} \)) were explained.
Fig. 1 (Left) The measurement scheme consisting of a chain of interferometers numbered from 0 to N. In the initial interferometer numbered (0) a controlled phase shift $\theta$ is inserted. In the subsequent interferometers the system interacts with the elements of environment prepared in a standard state, then a certain environment observable is measured, producing a series of measurement outcomes $i_1, \ldots, i_N$. Geometric phase acquired during propagation through the chain can be deduced from the detection probabilities in the output detectors $d_0$ and $d_1$.

(Right) The results of the calculation of geometric phases for different measurement records for a qubit system interacting with qubit environment via controlled phase-shift $\phi$ (environment qubit is a taget, system qubit acts as control) for N=6, so the total number of different measurement histories is $2^6$.

References
Optimization of stabilization modes for optical frequency standards based on the saturated absorption resonance

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At the present time, frequency standards and atomic clocks based on them are important and valuable quantum devices that have a wide range of applications in many areas of science (tests of fundamental theories, high-precision measurements) and technology (navigation, communication systems and transmission of information) [1]. One of the widespread optical (including transported) frequency standards are He–Ne and Nd:YAG lasers stabilized by saturated absorption resonances (SARs) on vibrational-rotational transitions of methane and iodine molecules [2, 3]. The advantages of these standards are small dimensions combined with a rather high frequency stability value [4–6].

Most often, SARs are used in practice in the configuration of two counter light waves of the same frequency (standing wave) interacting with the common transition in the atom (in the molecule). Herewith, in the absorption spectrum of one of the waves (the probe field), the SAR is observed in the form of a narrow dip (in the center of a wide Doppler profile), which can be used as the frequency reference to stabilize optical frequency standards.

The main purpose of investigations dedicated to frequency standards is to increase their stability, which can be achieved by optimizing frequency stabilization modes. In papers [7–9] it is shown that the error signal slope significantly depends on the parameters of harmonic frequency modulation (on the index and modulation frequency) used in stabilization systems. This slope is one of the main parameters determining the metrological characteristics (stability and accuracy) of frequency standards [10]. Therefore, maximizing the slope is an important task. However, a detailed theoretical study of this issue, which requires finding a dynamic solution for the density matrix, has not been carried out previously. In this work, we fill this gap by using for calculations the newly developed method [11], which allows us to construct an exact periodic solution of the equation for the density matrix without applying Fourier analysis. As a model, we consider the interaction of the frequency-modulated field of two counter waves with gas of two-level atoms. We numerically calculate the error signal in a wide range of laser-field frequency modulation parameters and determine the optimal stabilization modes of the frequency for which the error signal has a maximum slope. It was found that the presence/absence of harmonic modulation of the frequency in the pump field dramatically affects the optimal parameters of frequency modulation of the stabilization modes, but practically does not influence on the maximum value of the error signal slope.

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References
Laser thermometry of active elements of high power laser amplifier

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Recently, progress in laser systems that generate at the same time high average and high peak power radiation enables to access a fundamentally new physical domain of laboratory astrophysics and laser nuclear physics, as well as the design of the sources of pumping of optical parametric amplifier for high harmonic generation [1]. This makes researches aimed to development of high average-high peak power laser systems very actual.

A high power diode pumped multidisk closed-loop cryogenically cooled Yb:YAG laser amplifier is being developed [2]. The amplifier is an important part of the all diode-pumped all solid state laser system. The system aims to produce sub-Joule level pulses at pulse rate of 1 kHz [3]. The amplifier consists of eight diffusion-bonded YAG-Yb:YAG disks with 10 at.% of dopant concentration. The diameter of the disk is 25 mm, and its total thickness is 5.75 mm, with 2 mm of undoped medium. The multidisk laser amplifier is expected to amplify pulses energy from 10 mJ to 300 mJ pulses with 1 kHz repetition rate [4].

Usually, one has to relate to the data obtained from a thermal sensor installed in vicinity, however, it can be shown that the actual temperature in the pumped volume is significantly higher than surrounding media. To estimate the average temperature of the Yb-doped active element in the pumped volume, a simple method is proposed. The first step is measuring the absorption coefficient dependency on the temperature at the amplification wavelength. The next step is to carry out regular small signal amplification experiment. When the pump is turned off, there are two concurring processes that affect absorption: decay of laser level population and thermalisation of the medium. So, the experimental setup is very robust: one need to measure absorption coefficient dependency on temperature, then to carry out regular small-signal amplification experiment. Moreover, one can adapt this method to any active element which has temperature dependent absorption wavelength.

The dependency of transmitted power on the temperature during slow cooling process (~0.1 K/s) is measured. There is a strong dependence in range 120-300 K and quite sharp falloff in range 50-100 K. In the next experiment we used diode pump with 200 W of peak power, 1 kHz repetition rate and duty cycle of 50%. After the copper heatsink has reached stady-state temperature of ~155.7 K, we have turned off the pump and measured the dynamics of power transmittance. The relative transmittance during cooling process at 156 K is ~0.84, and the minimal value during thermalisation is ~0.56, which corresponds to ~210 K. It essentially means that the temperature distribution is non-uniform.

An indirect measuring method of the temperature inside the pumped volume of a cryogenically cooled active element of a high-power laser amplifier is proposed and experimentally implemented. All the data obtained are used for further augmentation and development of the all diode-pumped cryogenically cooled all solid state laser system operating with 1 kHz repetition rate.

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References:
The study of the nature of photophysical and photochemical processes proceeding in the photocatalytic oxidation with participation of the complexes of oxygen with photocatalysts titanium dioxide and tungsten trioxide are of great interest. The most powerful techniques for the study of elementary photoinduced processes are used in the conditions of molecular beam. In this work titanium and tungsten oxides were generated directly in the molecular beam, since in common conditions they are not volatile. Oxides were prepared by two methods: with photodecomposition of volatile compounds and by ablation. Volatile hexacarbonyl tungsten W(CO)₆ and titanium isopropoxide Ti(OC₃H₇)₄ were used in the first method and Ti and W foil, TiO crystal and pressed TiO₂ and WO₃ were used in ablation. For photoexcitation of precursor substances and photoionization of the formed photoproducts the radiation of solid-state Nd:YAG laser at the wavelengths of 266 and 532 nm was used. Photoproducts were detected with the time-of-flight mass-spectrometry. In Figure 1 the example of the mass-spectrum of photofragments is presented.
Generalized autobalanced Ramsey spectroscopy

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Atomic clocks are based on high-precision spectroscopy of isolated quantum systems and are currently the most precise scientific instruments. Fractional frequency instabilities and accuracies at the level of $10^{-18}$ have already been achieved, with the goal of $10^{-19}$ on the horizon [1]. Frequency measurements at such a level could enable new tests of quantum electrodynamics and cosmological models, searches for drifts of fundamental constants, and new types of chronometric geodesy [2].

For some of the promising clock systems, a key limitation is the frequency shift of the clock transition due to the excitation pulses themselves (probe-field-induced shift). In particular, for ultranarrow transitions (e.g., electric octupole [3] and two-photon transitions [4, 5]), the off-resonant ac-Stark shift can be so large in some cases that high-accuracy clock performance is not possible. In the case of magnetically induced spectroscopy [6, 7], these shifts (quadratic Zeeman and ac-Stark shifts) could ultimately limit the achievable performance. A similar limitation exists for clocks based on direct frequency comb spectroscopy [8, 9] due to off-resonant ac-Stark shifts induced by large numbers of off-resonant laser modes. In addition to optical standards, probe-field-induced shifts can create significant instability for atomic clocks in the microwave range based on coherent population trapping (CPT) [10-12].

In this work, we present a method of generalized autobalanced Ramsey spectroscopy (GABRS) for the suppression of the probe-field-induced shifts in atomic clocks. Our method uses a two-loop approach to feedback on and stabilizes the clock frequency $\omega$ as well as a second (concomitant) parameter $\xi$, which is an adjustable property of the first and/or second Ramsey pulses $\tau_1$ and $\tau_2$. To determine the error signals, it is necessary to use Ramsey sequences (see Fig. 1) with two different dark times $T_1$ and $T_2$. The operation of GABRS consists of the correlated stabilization of both variable parameters $\omega$ and $\xi$. For stabilization of the frequency $\omega$ we need to form an error signal (differential signal). In our approach, we use phase jumps $\alpha_+$ and $\alpha_-$ of the probe field before the second pulse $\tau_2$ (see Fig. 1).

![Fig. 1](image_url)

\textit{Fig. 1} a) Schematic illustration of a sequence of two arbitrary Ramsey pulses (with the real amplitude $\mathcal{E}(t)$ and durations $\tau_{1,2}$) which are separated by the dark time $T$. b) Scheme of the clock transition $|g\rangle \leftrightarrow |e\rangle$ (with unperturbed frequency $\omega_{\text{clock}}$) interacting with the probe field at the frequency $\omega$.

The main idea of GABRS is the following. First of all, apart from frequency $\omega$ for the frequency stabilization procedure we will use some additional (concomitant) variable parameter $\xi$, which is related to the first and/or second Ramsey pulses $\tau_1$ and $\tau_2$. For example, the parameter $\xi$ can be equal to the phase $\phi_\xi$ of the second pulse as it was proposed in [14]. However, there are many other variants of the
concomitant parameter $\xi$ (e.g., frequency step, pulse duration and etc.) Thus, the error signal in should be considered as a function of two variable parameters: $S_t^{(\text{err})}(\omega, \xi)$. Secondly, we will use the Ramsey interrogation of the clock transition for two different, fixed intervals of free evolution $T_1$ and $T_2$, i.e., we will use two error signals $S_t^{(\text{err})}(\omega, \xi)$ and $S_t^{(\text{err})}(\omega, \xi)$. For GABRS, the procedure for the frequency stabilization is organized as a series of the following cycles. For interrogation with dark time $T_1$, the parameter $\xi$ is fixed, and we stabilize the variable frequency $\omega$ at the zero point of the error signal: $S_t^{(\text{err})}(\omega, \xi, t_{\text{fixed}}) = 0$. After this procedure, we switch to interrogation with dark time $T_2$, where we fix the previously obtained frequency $\omega$ and stabilize the variable parameter $\xi$ at the zero point of the second error signal: $S_t^{(\text{err})}(\omega, \xi, t_{\text{fixed}}) = 0$. If we continue these cycles, then the final result (formally for $t \rightarrow \infty$) consists of the stabilization of both parameters, $\omega = \omega_0$ and $\xi = \xi_0$, which correspond to the solution of a system of two equations:

$$S_t^{(\text{err})}(\omega, \xi) = 0, \quad S_t^{(\text{err})}(\omega, \xi) = 0$$

in relation to the two unknowns $\omega$ and $\xi$. It can be shown that (1) always contains the solution $\omega = \omega_{\text{clock}}$ (where $\omega_{\text{clock}}$ is unperturbed clock frequency, see Fig. 1).

Note, in addition to the suppression of probe-field-induced shifts, the GABRS technique is protected against various processes of decoherence and also technical issues including time-dependent pulse area fluctuations (even more powerful than the common weak pulse area variation from previous schemes) and phase-jump modulation errors needed to generate the error signal.

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References

Optimization of deep laser cooling of atoms on narrow-line optical transitions in standing wave

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The theoretical description of the kinetics of neutral atoms in the polarized light fields with all the atomic levels, the coherence, the recoil effect is both important and challenging problem. The first step toward understanding mechanisms of interaction between atoms and light was called quasi-classical approach. [1,2] It lies in the fact that the equations for the density matrix can be reduced to the Fokker-Planck equation for the Wigner function in the phase space. But the semiclassical approximation is inapplicable for investigating the cooling of atoms at clock transitions, because the quasiclassical parameter (the recoil frequency) is not small (in comparison with the natural line width). Later quantum methods were developed [3], for example, the secular approach which describes cooling and localization of atoms in the optical potential. Secular approximation fails high vibrational levels and for atoms in high vibrational states.

We have developed an own quantum method [4] to obtaining the stationary distribution of two-level atoms in a standing wave of arbitrary intensity, allowing full account the recoil effects. The quasiclassical regimes of laser cooling of atoms have been studied in sufficient detail, but the attention given to quantum regimes is not enough. Hundreds of calculations for Ca, Sr, Mg have been carried out which have made it possible to reveal some interesting and completely new regularities that open up new prospects for laser cooling of atoms on weak optical transitions. If in the semiclassical regime the Rabi frequency ($\Omega_0$), detuning ($\delta$) and recoil frequency ($w_r$) is conveniently expressed in units of spontaneous relaxation ($\gamma$), then in the quantum ($w_r \sim \gamma$) and ultraquantum ($w_r \gg \gamma$) it changes radically. If we express these parameters in units of recoil frequency, then we obtain the absolute universality of stationary distributions of $^{24}\text{Mg}$ ($w_r = 1100\gamma$), $^{40}\text{Ca}$ ($w_r = 32.3\gamma$), $^{88}\text{Sr}$ ($w_r = 0.635\gamma$) atoms cooled on optical transitions (Fig.1). Narrow peaks in the momentum distribution are the manifestation of a selective coherent population trapping rate (VSCPT) at points corresponding to the momentum of one photon, observed in a weak light field.

\[ \begin{align*}
\text{Fig. 1} & \quad \text{The steady-state state momentum distribution of different atoms (}^{24}\text{Mg, }^{40}\text{Ca, }^{88}\text{Sr). Light field detuning: } \\
& \quad \delta = -3w_r. \text{ Rabi frequency of one wave: a) } \Omega_0 = 0.64w_r \text{ b) } \Omega_0 = 6.4w_r. 
\end{align*} \]

A minimum temperature of laser cooling in a weak light field was searched (Fig.2). Fig. 2a shows the impulse distributions for various detunings. In case of small detuning, extremely strong manifestations of VSCPT can be observed at points corresponding to the momentum of one photon. The minimum temperature of the impulse distribution is reached when the detuning is equal, in absolute value, to three units of the recoil frequency.
The time and kinetic energy of atoms as a function of the intensity of the light field is shown in Fig 3. The cooling time is determined by the slowest processes of evolution of atomic density matrix. In semiclassical limit it is scaled by $w^{-1}$ units. In quantum regime of laser cooling the cooling time can be expressed in universal form for different atoms and scaled in by $\gamma^{-1}$ units. The cooling time depends on the width of the initial momentum distribution of the atoms. Initial momentum distribution for magnesium atoms is of the order of 1 mK. For a larger initial temperature, the time increases linearly.

Investigation show that there is a narrow region of intensity of the light field, which allows dramatically reduce the time of laser cooling and achieve ultra-low temperatures, on the order of 3 - 15 μK. The most significant result of the research is the complete equivalence of time, temperature, and stationary impulse and spatial distributions of various atoms cooled on clock optical transitions, with the correct choice of the frequency of the detuning of the light field $\delta = -3w_r$. Which in turn, enables the cooling of magnesium atoms by a standing light wave that had previously been considered impossible.

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