Ground-state electromagnetically-induced-transparency cooling of $^{171}Yb^+$ ions in a polychromatic field

D. S. Krysenko,[1,2] O. N. Prudnikov,[1,3,*] A. V. Taichenachev,[1,3] V. I. Yudin,[1,2,3] S. V. Chepurov,[1] and S. N. Bagaev[1]

[1]*Institute of Laser Physics, 630090 Novosibirsk, Russia*
[2]*Novosibirsk State Technical University, 630073 Novosibirsk, Russia*
[3]*Novosibirsk State University, 630090 Novosibirsk, Russia*

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We propose a scheme of deep laser cooling of $^{171}\mathrm{Yb}^+$, which is based on the effect of electromagnetically induced transparency (EIT) in a polychromatic field with three frequency components resonant with optical transitions of the $^2S_{1/2} \to {}^2P_{1/2}$ line. The deep cooling down to the ground motional state in a trap allows for a significant suppression of the second-order Doppler shift in the frequency standard. Moreover, in our scheme, there is no need to use a magnetic field, which is required for Doppler cooling of $^{171}\mathrm{Yb}^+$ in a field with a two frequency component. Cooling without the use of a magnetic field is important for the deep suppression of quadratic Zeeman shifts of clock transitions due to an uncontrolled residual magnetic field.

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I. INTRODUCTION

Laser cooling is a necessary step for modern experiments with quantum systems based on neutral atoms and ions that have wide applications, including quantum metrology, the study of the fundamental properties of cold atomic Bose and Fermi condensates [1–4], the implementation of quantum logic elements, and quantum computing [5]. The development of modern frequency standards using cold atoms [6–8] and ions [9–11] has become highly relevant. The achieved level of accuracy and long-term stability of optical frequency standards at the level 10^{-18} opens up new horizons for modern fundamental research, such as the study of the effects of Earth's gravitation on the space-time continuum [7,8,12], the test of fundamental constants [13,14], verification of the general relativity, Lorentz invariance of space [15–17], the search for dark matter [18,19], etc.

To achieve a high-precision level of frequency standards, it is necessary to take into account systematic frequency shifts of a different nature. Therefore, works aimed at the suppression of these shifts are very important. For example, in the context of the $^{171}\mathrm{Yb}^+$ ion-based frequency standard, further progress can be linked to the control and suppression of systematic shifts caused by a residual magnetic field, blackbody radiation (BBR) shifts, and quadratic Doppler shifts [10,16]. However, the main challenge here is that the transition $^2S_{1/2} \to {}^2P_{1/2}$ used for laser cooling is not closed, which requires the use of a laser field with at least two frequency components [20–22] (see Fig. 1). In this case, a relatively large magnetic field of $\sim$1–10 G is required to destroy the coherent trap state at the $^2S_{1/2}(F=1)$ level via a $^2S_{1/2}(F=1) \to {}^2P_{1/2}(F=0)$ optical transition due to a coherent population trapping (CPT) effect. The laser cooling here can reach a minimum temperature that corresponds to the Doppler limit $k_B T_D \simeq \hbar\gamma/2$, where γ is the natural linewidth of the optical transition $^2S_{1/2} \to {}^2P_{1/2}$. The hysteresis effects during switching off the magnetic field as required for cooling create certain difficulties in minimizing the residual magnetic field and keeping it constant in various cooling and clock operation cycles. Similar difficulties arise when implementing quantum logic and quantum computing elements based on $^{171}\mathrm{Yb}^+$ ions [23].

In this paper, we propose an alternative method of laser cooling that makes it possible to eliminate the use of a magnetic field and, in contrast to the standard scheme [20–22], allows atoms to be cooled significantly below the Doppler limit T_D, thus significantly suppressing the second-order Doppler shift in a frequency standard.

II. DEEP LASER COOLING OF $^{171}\mathrm{Yb}^+$

For laser cooling of a $^{171}\mathrm{Yb}^+$ ion, a light field with at least two frequency components has to be used [20–22] (see Fig. 1). Here, one of the frequency components is close to the $^2S_{1/2}(F=0) \to {}^2P_{1/2}(F=1)$ transition, and the other one to the $^2S_{1/2}(F=1) \to {}^2P_{1/2}(F=0)$ transition. The laser cooling arises as a result of the action of the dissipative Doppler force on a moving ion, which leads to cooling only to the temperature of the Doppler limit $k_B T_D = \hbar\gamma/2$. In this scheme, an additional magnetic field is required to destroy the coherent trap state at the $^2S_{1/2}(F=1)$ level via a $^2S_{1/2}(F=1) \to {}^2P_{1/2}(F=0)$ optical transition due to the CPT effect [21,22].

Deeper laser cooling of ions, down to the ground motional state, can be achieved under conditions of resolved sideband cooling [24–26], when the ion is localized in a trap on scales smaller than the wavelength (the Lamb-Dicke parameter $\eta = \sqrt{E_R/\hbar\,\omega_{\mathrm{osc}}} \ll 1$, where $E_R = \hbar^2 k^2/2M$ is the recoil energy, and M is the ion mass), and ω_{osc}, the ion oscillation frequency in the trap, is large enough, $\omega_{\mathrm{osc}} \gg \gamma$ (i.e., transitions between different motional states of the ion have to be

*oleg.nsu@gmail.com

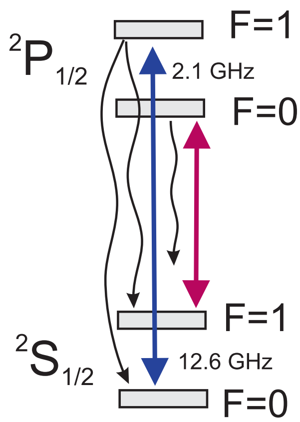

FIG. 1. The energy level of the hyperfine structure $^2S_{1/2}$ and $^2P_{1/2}$ in the $^{171}Yb^+$ ion, which is used for laser cooling. The solid lines represent the transitions induced by two frequency components of the field. The wavy lines represent the main channels of spontaneous decay. The magnetic field is required here to destroy the CPT effect (coherent trap state) on the $^2S_{1/2}(F = 1)$ level via a $^2S_{1/2}(F = 1) \to {}^2P_{1/2}(F = 0)$ optical transition.

spectrally resolved). However, these conditions are not satisfied for the $^2S_{1/2} \to {}^2P_{1/2}$ cooling transition in the $^{171}Yb^+$ ion, where the natural linewidth $\gamma/2\pi = 23$ MHz and the typical oscillation frequency in the trap $\omega_{\rm osc}/2\pi \simeq 400$–600 kHz.

Laser cooling by using the electromagnetically induced transparency (EIT) technique [27] does not require the condition $\omega_{\rm osc} \gg \gamma$. To implement it, a three-level Λ system is required, in which transitions are induced by a pair of light waves. Under conditions when the detunings of light waves are equal, the atoms are pumped into a dark state, which does not interact with the field. This allows to substantially suppress the heating processes associated with the emission of spontaneous photons. Moreover, the presence of a narrow EIT resonance, with a width much smaller than the spontaneous decay rate γ of an excited state, enables cooling via two-photon transitions between different motional states of the ground levels in the Λ scheme, similar to the Raman cooling technique [27–29].

The choice of interaction scheme for the implementation of EIT cooling of a $^{171}Yb^+$ ion is a nontrivial task. In Ref. [30], it was proposed to use three frequency components near the resonance of the optical transition $^2S_{1/2}(F = 1) \to {}^2P_{1/2}(F = 0)$, known as the double EIT scheme [31]. In this case, each frequency component determines transitions between different Zeeman levels of the ground state $|^2S_{1/2}, F = 1, \mu = 0, \pm1\rangle$ and the excited state $|^2P_{1/2}, F = 0, \mu = 0\rangle$. In addition, to repump from the $^2S_{1/2}(F = 0)$ state it is necessary to use an extra laser field resonant to the $^2S_{1/2}(F = 0) \to {}^2P_{1/2}(F = 1)$ transition. Thus the laser cooling scheme [30] requires four frequency components, which significantly complicates the overall scheme of laser cooling. As well, in a recent paper [32] a similar double EIT scheme for the laser cooling of $^{171}Yb^+$ was theoretically and experimentally investigated. Compared to Ref. [30], there only two frequency components resonant to the $^2S_{1/2}(F = 1) \to {}^2P_{1/2}(F = 0)$ transition are used, but it also requires a magnetic field to destroy the coherent trap state at the $^2S_{1/2}(F = 1)$ level. For

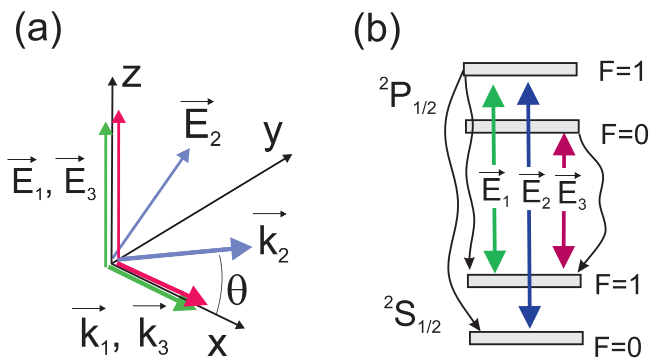

FIG. 2. (a) The three-frequency field configuration formed by three running waves. (b) The transitions induced by each frequency component.

both these cases additional optical pumping has to be carried out to prepare the initial clock state $^2S_{1/2}(F = 0)$.

To implement deep EIT cooling, as well as the preliminary Doppler cooling preceding it, we propose to use a polychromatic field of running waves with only three frequencies,

$$\mathbf{E}(\mathbf{r}, t) = \mathrm{Re}\left\{\sum_{p=1,2,3} \mathbf{E}_p e^{i\mathbf{k_p r}} e^{-i\omega_p t}\right\}, \tag{1}$$

where $\mathbf{E}_p$ are complex vectors, which define the polarization and amplitude of each frequency component $p = 1, 2, 3$.

In our configuration, the field components have linear polarizations [see Fig. 2(a)]. The wave vectors of the ω_1 and ω_3 frequency components are directed along the x axis, and their polarization vectors $\mathbf{E}_1$ and $\mathbf{E}_3$ are along the z axis. The wave vector of the ω_2 component lies in the (xz) plane with some angle θ to the x axis. The orientation of the polarization vector $\mathbf{E}_2$ is varied for different cooling stages. The frequencies ω_n are chosen so that they provide light-induced transitions between different hyperfine levels of the $^2S_{1/2}$ and $^2P_{1/2}$ states according to the scheme in Fig. 2(b).

A. Doppler cooling

As the EIT ground-state cooling technique is applicable to ions already prepared at low temperatures [27–29], a preliminary Doppler cooling is required. For the considered field configuration (1), an effective Doppler cooling can be realized with linear codirectional polarizations of the field components $\mathbf{E}_1||\mathbf{E}_2||\mathbf{E}_3$. In this case, the corresponding scheme of resonant light-induced transitions over the Zeeman sublevels is shown in Fig. 3(a). In Ref. [33], we carried out a detailed analysis of laser cooling in such a field. It was shown that the minimum temperature corresponds to the Doppler limit

$$k_B T = \hbar\gamma/3, \tag{2}$$

and is achieved for low intensities under the condition that the Rabi frequencies of each frequency component are equal, $\Omega_1 = \Omega_2 = \Omega_3$ ($\Omega_p = |\mathbf{E}_p|d/\hbar$, d is the transition dipole moment $^2S_{1/2} \to {}^2P_{1/2}$), and the detunings of each frequency component have to be chosen,

$$\delta_1 = \delta_2 = \delta_3 = -\gamma/2. \tag{3}$$

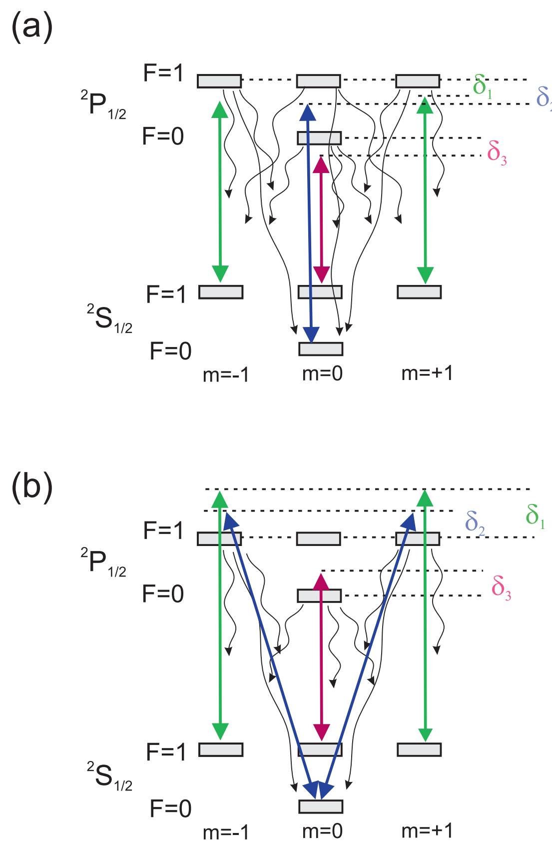

FIG. 3. The Zeeman sublevels of hyperfine states $^2S_{1/2}$ and $^2P_{1/2}$ of $^{171}\mathrm{Yb}^+$ and transitions induced by a frequency component of the light field for two cooling stages: (a) the first stage of Doppler cooling and (b) the second stage of EIT cooling. The transitions induced by the frequency components are indicated by double arrows: green—transitions caused by the $\mathbf{E}_1$ component; blue—transitions caused by the $\mathbf{E}_2$ component; and red—transitions caused by the $\mathbf{E}_3$ component of the light field. The wavy arrows indicate transitions caused by spontaneous decays. Here, δ_1, δ_2, and δ_3 are the corresponding detunings for the frequency components.

Here, the detunings are defined as $\delta_p = \omega_p - \omega_{0p}$, the difference between the frequency of the pth field component $\mathbf{E}_p$ and the frequency of the corresponding resonant transition ω_{0p} (see Fig. 3).

B. Ground-state EIT cooling

For the second stage of deep laser cooling in the proposed field configuration shown in Fig. 2(a), we direct the polarization vector $\mathbf{E}_2$ along the y axis so that $\mathbf{E}_2 \perp \mathbf{E}_{1,3}$. In this case, the interaction with light components forms a double Λ scheme for the Zeeman sublevels of hyperfine states $^2S_{1/2}$ and $^2P_{1/2}$ [see Fig. 3(b)] that allows to implement the EIT ground-state cooling technique. For EIT cooling in the considered scheme, it is necessary to choose the detuning of the driven field component $\mathbf{E}_1$ to be blue detuned, $\delta_1 > 0$. The intensity of this component has to be chosen so that the ac Stark shifts of dressed Zeeman sublevels $|^2S_{1/2}, F = 1, m = \pm 1\rangle$ are light-shifted upwards by an amount equal to the trap frequency $\omega_{\rm osc}$. The field components $\mathbf{E}_2$ and $\mathbf{E}_1$ drive two-photon transitions between the ground states $|^2S_{1/2}, F = 1, m = \pm 1\rangle$ and $|^2S_{1/2}, F = 1, m = 0\rangle$. For the condition $\delta_2 = \delta_1$, an efficient EIT cooling down to the ground motional state can be achieved, similar to three-level Λ atomic system [27–29]. The third frequency component $\mathbf{E}_3$ plays the role of optical pumping for depopulating the state $|^2S_{1/2}, F = 1, m = 0\rangle$.

The dynamics of the average vibrational quantum number $\bar{N} = \sum_{n=0}^{\infty} nP_n$ (where P_n is the population of the ion's nth motional state in the trap) is determined by the rate balance equation [26,29]

$$\frac{d}{dt}\bar{N} = -(A_- - A_+)\bar{N} + A_+, \tag{4}$$

where the rate coefficients $A_\pm$ in accordance with Ref. [26] are given by the scattering rate $W(\Delta)$ as a function of two-photon detuning for an atom at rest, $\Delta = \delta_2 - \delta_1$. The scattering rate can be expressed trough the steady-state population ρ^{ee} in the excited state $^2P_{1/2}$,

$$W(\Delta) = \gamma\, \rho^{ee}. \tag{5}$$

Thus the rate coefficients can be expressed as

$$A_\pm = \eta^2 [W_0 + W_\mp], \tag{6}$$

where

$$W_0 = W(0), \tag{7}$$

and

$$W_\pm = W(\pm\omega_{\rm osc}). \tag{8}$$

Ion cooling is achieved under conditions $A_- > A_+$. In this case, the stationary solution of Eq. (4) has the form

$$\bar{N}_f = \frac{A_+}{A_- - A_+} = \frac{W_0 + W_-}{W_+ - W_-}, \tag{9}$$

and determines the minimum laser cooling temperature of the ion in the trap. The Lamb-Dicke parameter for two-photon transitions is determined by the difference between the wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$,

$$\begin{aligned}\eta &= |(\mathbf{k}_1 - \mathbf{k}_2)\cdot \mathbf{e}_m| \sqrt{\frac{\hbar}{2M\omega_{\rm osc}^{(m)}}} \\ &\approx |(\mathbf{n}_1 - \mathbf{n}_2)\cdot \mathbf{e}_m| \sqrt{\frac{\hbar k^2}{2M\omega_{\rm osc}^{(m)}}},\end{aligned} \tag{10}$$

where $\mathbf{e}_m$ denotes the unit vector describing the oscillation direction of the spatial mode to be cooled and $\omega_{\rm osc}^{(m)}$ is the oscillation frequency of this spatial mode [27], $\mathbf{n}_j = \mathbf{k}_j/|\mathbf{k}_j|$ $(j = 1, 2)$, where we assume $|\mathbf{k}_1| \simeq |\mathbf{k}_2| = k$. Thus, by varying the angle θ between the wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$ (see Fig. 2), as well as the overall direction of the waves relative to the principal axes of the trap, it is possible to control the laser cooling rate of different motional modes.

The expressions for the decay rates W_0, W_+, and W_- can be obtained by solving the density matrix (Bloch equations) for the Yb ion [33]. For the transition scheme in Fig. 3(b), where $\mathbf{E}_2 \perp \mathbf{E}_{1,3}$, we get the following expression for the total population of the excited state $^2P_{1/2}$ and respectively $W(\Delta)$,

$$W(\Delta) = \gamma \frac{108\, \Delta^2\, \Omega_1^2\, \Omega_2^2}{D}, \tag{11}$$

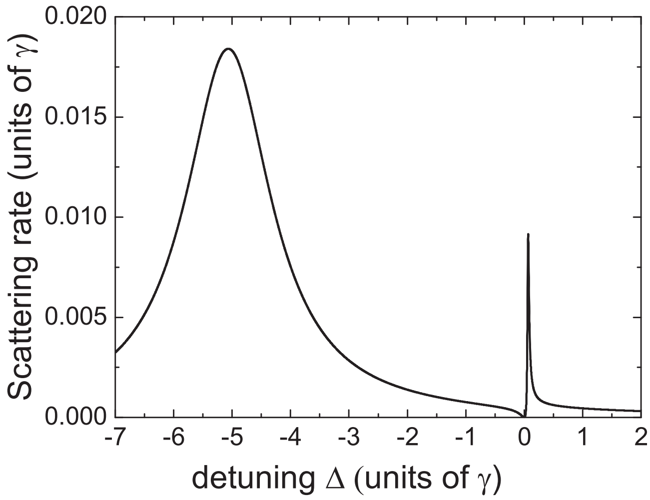

FIG. 4. The scattering rate $W(\Delta)$ as a function of two-photon detuning. The field parameters are $\delta_1 = 5\gamma$, $\Omega_1 = 2\gamma$, $\Omega_2 = 0.2\gamma$, $S_3 = 0.5$.

where

$$D = 2\,\Omega_1^6 + \left(\frac{13}{2}\Omega_2^2 - 48\,\delta_2\Delta\right)\Omega_1^4 + \left(7\,\Omega_2^4 + 72\,\Delta^2\left[3\,\Omega_2^2 + \gamma^2/4 + 4\,\delta_2^2\right]\right)\Omega_1^2 + \frac{5}{2}\,\Omega_2^2\left(\Omega_2^4 + 24\,\delta_1\Delta\,\Omega_2^2 + \frac{288}{5}\Delta^2(\gamma^2 + 4\,\delta_1^2)\right) + 108\,\Delta^2\frac{\Omega_1^2\Omega_2^2}{S_3}. \quad (12)$$

Here, $S_3 = \Omega_3^2/(\gamma^2 + 4\,\delta_3^2)$ is the saturation parameter for the $\mathbf{E}_3$ component. Under conditions $\Omega_1 \gg \Omega_2$ and $\delta_1 \gg \gamma$ ($\delta_1 > 0$), the scattering rate has the form shown in Fig. 4, which is typical for the EIT laser cooling technique [26].

As can be seen from Fig. 4, the point $\Delta = 0$ corresponds to the CPT condition. The narrow bright resonance appearing to the right of the CTP point corresponds to the two-photon resonance between the sublevels of the ground state. Its shift from $\Delta = 0$ is determined by the ac Stark shift Δ_{ac} of the dressed-state Zeeman sublevels $|^2S_{1/2}, F = 1, m = \pm 1\rangle$ and $|^2S_{1/2}, F = 0, m = 0\rangle$. For the considered case, the $\mathbf{E}_1$ component is chosen as a drive field, i.e., under the condition $(\Omega_1, \delta_1) \gg \Omega_2$, we have

$$\Delta_{ac} = \left(\sqrt{\Omega_1^2/3 + \delta_1^2} - \delta_1\right)/2. \quad (13)$$

The condition

$$\Delta_{ac} = \omega_{osc} \quad (14)$$

is optimal for the two-photon transitions involved in changing the vibrational number to $\Delta n = -1$, and thus resulting in the highest cooling rate and the lowest temperature [26,27]. This determines the intensity of the $\mathbf{E}_1$ component for given δ_1 and ω_{osc}:

$$\Omega_1 = 2\,\sqrt{3}\sqrt{\omega_{osc}(\delta_1 + \omega_{osc})}. \quad (15)$$

The obtained analytical expression (11) allows us to estimate the limit of laser cooling of the $^{171}Yb^+$ ion in the proposed EIT scheme. In particular, the average vibrational number (9) in the limit $\Omega_1 \gg \Omega_2$ takes the form

$$\bar{N}_f = \frac{3\,\Omega_2^2/2 + S_3\gamma^2}{16\,\delta_1^2\,S_3}, \quad (16)$$

which, for low intensity of the $\mathbf{E}_2$ component, when $\Omega_2 \ll \sqrt{2\,\gamma S_3/3}$, leads to

$$\bar{N}_f = \frac{\gamma^2}{16\,\delta_1^2}. \quad (17)$$

Therefore, deep laser cooling of a $^{171}Yb^+$ ion down to $\bar{N}_f \ll 1$ can be achieved under the condition $\delta_1 \gg \gamma$. Note that expression (17) corresponds to the well-known limit of EIT cooling in the standard Λ scheme [26].

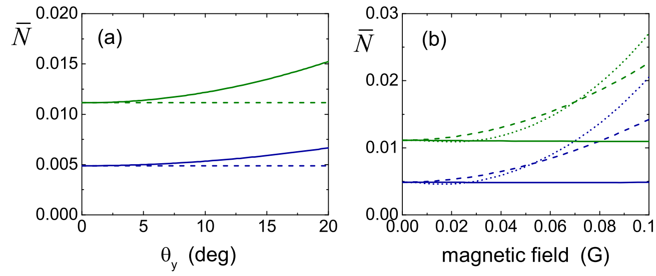

FIG. 5. EIT cooling limit average quantum number $\bar{N}$ against possible experimental imperfections: (a) as a function of angle θ_y describing the deviation of the $\mathbf{E}_2$ component light polarization from the y axes [dashed lines represent results for $\mathbf{k}_2$ chosen along the z axis ($\theta = \pi/2$) and the solid lines represent results for $\theta = \pi/4$], and (b) as the function of residual magnetic field (solid lines—magnetic field along x; dashed lines—magnetic field along y; and dotted lines—magnetic field along z). Green (upper) lines represent results for the field parameters $\delta_1 = \delta_2 = 5\gamma$, $\Omega_1 = 1.25\gamma$, and blue (lower) lines for the field parameters $\delta_1 = \delta_2 = 10\gamma$, $\Omega_1 = 1.77\gamma$. The other parameters $\Omega_2 = 0.1\gamma$, $\delta_3 = 0$, $S_3 = 0.5$ are kept the same. Here, $\omega_{osc}/2\pi = 600$ kHz for the considered $^{171}Yb^+$ trap.

III. DISCUSSION

In the following section we discuss some issues related to the experimental realization of the proposed scheme and its resilience against unavoidable experimental imperfections. First, we note that the cooling rate is determined by the Lamb-Dicke parameter for the two-photon transition (10). It contains the Lamb-Dicke parameter for the one-photon transition $\eta_1 = \sqrt{k^2\hbar/(2M\omega_{osc})}$ and the factor depending on the angle between the wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$. For our $^{171}Yb^+$ trap with $\omega_{osc}/2\pi \simeq 600$ kHz, we have $\eta_1 \simeq 0.1$. Thus, in order to achieve a reasonable cooling rate, the angle θ between the wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$ [see Fig. 2(a)] should be large, close to $\pi/2$.

Figure 5 demonstrates the EIT cooling limit $\bar{N}$ for the Yb ion and its sensitivities to experimental imperfections caused by the deviation of the $\mathbf{E}_2$ component light polarization from the y axes and the presence of a residual magnetic field. As can be seen, the results are resistant to the above imperfections. Indeed, for the angle $\theta = \pi/2$ there is no dependence on the deviation of the $\mathbf{E}_2$ component light polarization from the y axes. For the case of $\theta = \pi/4$, the average quantum number $\bar{N}$

increases slightly, but remains small enough for a wide range of θ_y. The residual magnetic field required for metrology clock operations is in the order of 0.01 G. As can be seen from Fig. 5(b), such values of the magnetic field have no effect on the EIT cooling limit.

We emphasize that the suggested EIT cooling scheme does not require a magnetic field at all. This opens up possibilities for developing techniques for more deep control of the residual magnetic field inside the trap to the level ∼0.001 G, which potentially allows to reduce the instability of optical clocks due to the second-order Zeeman shift to the level of 10^{-19} and below.

The cooling rate of the presented EIT scheme is reasonable enough and comparable to the double EIT cooling scheme implemented in Ref. [32]. As an example, for the field parameters corresponding to the green and blue lines in Fig. 5 for $\theta = \pi/2$, the cooling rates are $\dot{\bar{N}} \simeq 8.2$ ms^{-1} and $\dot{\bar{N}} \simeq 4.6$ ms^{-1}, respectively.

Finally, we also note that an additional advantage of the presented EIT laser cooling scheme, since $\Omega_2 \ll \Omega_1$, is that the ion is localized on the lower vibrational state of the $^2S_{1/2}(F=0)$ state, which is directly used for further implementations of clock protocols with quadrupole $^2S_{1/2}(F=0) \to {}^2P_{3/2}(F=2)$ or octupole $^2S_{1/2}(F=0) \to {}^2F_{7/2}(F=3)$ transitions.

IV. CONCLUSION

We propose an EIT scheme for the ground-state laser cooling of ^{171}Yb$^+$ ions that does not require the use of a magnetic field. For laser cooling, a polychromatic configuration of the light field is used, consisting of three monochromatic running waves resonant to optical transitions of the $^2S_{1/2} \to {}^2P_{1/2}$ line. For the first stage of Doppler cooling, the light frequency components are running waves with codirectional linear polarizations. In this case, each of the frequency components of the field has a mechanical action on the ion, which finally leads to cooling down to the temperature of the Doppler limit. For the trap with a typical oscillation frequency of about 600 kHz, this temperature corresponds to the average vibrational quantum number $\bar{N} \simeq 20$. To implement the second stage of deep laser cooling down to the motional ground state, i.e., $\bar{N} \ll 1$, the polarization of one of the frequency components has to be oriented relative to the others by an angle of 90°.

On the one hand, the exclusion of the magnetic field from laser cooling allows to reduce the total time of the "clock operation" cycle by eliminating the time interval required to turn off and attenuate the magnetic field, which is used in a standard two frequency field cooling scheme. Indeed, reducing the cycle time contributes to a faster accumulation of measurement statistics in optical frequency standards. On the other hand, the absence of the need to use a magnetic field for the cooling process allows for more accurate control of the residual magnetic field and minimizes its fluctuations in various measurement cycles, which is important for further improving the accuracy and long-term stability of optical atomic clocks based on ^{171}Yb$^+$. In addition, deep ground-state cooling to $\bar{N} < 1$ significantly suppresses the second-order Doppler shift to a level below $\Delta\nu/\nu < 10^{-19}$, which allows us to remove it from the uncertainty budget of frequency standards based on ^{171}Yb$^+$.

Note that the suggested method of the ground-state cooling is also important for quantum logic elements based on cold ^{171}Yb$^+$ ions.

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