Nearly Nondestructive Thermometry of Labeled Cold Atoms and Application to Isotropic Laser Cooling

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We develop a form of nondestructive optical thermometry to deterministically measure the temperature of the selected segment of a cold-atom ensemble. The essence is to monitor the thermal expansion of the targeted cold atoms after their labeling through manipulation of the internal states, and the nondestructive property relies on nearly lossless detection via the driving of a cycling transition. The temperature information is extracted from the change of densities via a bucket detector without the necessity of a complicated imaging setup. We also focus on the application of this method to isotropic laser cooling, and it has the capability of addressing only the atoms on the optical detection axis within the enclosure, which is readily compatible with typical configurations of atomic clocks or quantum sensing. Our results confirm the sub-Doppler-cooling features of isotropic laser cooling, and we further investigate the relevant cooling properties. Furthermore, we demonstrate the recently developed optical configuration with injection of cooling-laser light in the form of hollow beams, which helps to enhance the cooling performance and accumulate more cold atoms in the central regions.

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I. INTRODUCTION

Ever since the advent of laser cooling and trapping [1,2], cold atoms have become a key platform in emerging quantum technologies, including quantum precision measurement [3], quantum sensing [4], quantum simulation [5–7], and quantum information [8,9]. Over the last three decades, intense efforts have been devoted to the development of relevant technologies, where deterministic measurement of cold atoms' temperature is an essential subject [10,11]. So far, time-of-flight (TOF) measurement of falling atoms has become the standard technique to evaluate the temperature under various scenarios, such as optical molasses, magneto-optical trapping (MOT), and a Bose-Einstein condensate (BEC) [12,13]. Nevertheless, recent progress raises demands for different types of temperature-measurement techniques, especially for situations not so favorable for the TOF method. For example, there has been much interest in the thermometry of cold atoms in experiments regarding cavity quantum electrodynamics [14], ultracold atoms on the nanokelvin scale [15–17] or subject to strong interactions [18,19], and many other interesting cases in cold-atom physics [20–22]. Moreover, nondestructive thermometry of cold atoms [23] also draws a lot of attention, and a recent study further demonstrates the possibility of the nondestructive temperature measurement technique for a BEC [24].

Isotropic laser cooling (ILC) in the form of cold atoms enclosed in an environment of diffuse-reflection light [25–29] has found critical applications in microwave atomic clocks, spectroscopic studies, and quantum sensors [30–36] due to its characteristics of compactness and robustness [32,34]. To ensure the quality of the diffuse optical field of ILC, the enclosure of the diffuse-reflection surface around the atoms needs to cover nearly the entire 4π solid angle. Therefore, unlike the typical case of six-beam optical molasses or MOT, if we want to apply the TOF method to ILC [28,29], an extra falling distance and an auxiliary chamber equipped with a detection windows are necessary, which results in considerable difficulties compared with the natural requirement of the ILC platform. On the other hand, it is also practically troublesome to incorporate a transparent window to image the entire ensemble, such that fluorescent light is not likely an ideal option for the signal of temperature measurement either. Therefore, it remains a challenge to find a method that not only gives accurate results but that is also

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straightforward to implement and integrate for temperature assessment of ILC.

In this article, we report our recent progress in realizing and characterizing a method to directly measure the temperature of a selected segment of cold atoms via detection of their thermal expansion after their labeling. The expansion process is monitored on the basis of the absorption of light from a probe laser, and the collective information on the density change in time is extracted via a bucket detector without the necessity of imaging. This method is applicable to most types of cold-atom platforms, and here we emphasize its application to ILC experimentally. First, we present the basic principles and typical operation procedures. Then we perform further investigations with the nearly-nondestructive-detection process. Finally, according to the results of temperature assessment, we investigate the elementary properties of ILC's sub-Doppler-cooling effects.

II. BASIC MECHANISM AND IMPLEMENTATION

The basic mechanism and implementation are outlined in Fig. 1. In the experiment, ^{87}Rb atoms are laser cooled by the diffuse-reflection light inside a cylindrical cavity [36–38]. The cylindrical cavity is made of a glass cell with inner diameter of 54 mm and height of 54 mm, and its surface is coated with a reflective material whose diffuse-reflection index is more than 98% at the wavelength of 780 nm. The cooling light is red detuned at 22.5 MHz to transition $5^2S_{1/2}, F = 2 \leftrightarrow 5^2P_{3/2}, F = 3$. The repumping light, tuned close to the resonance $5^2S_{1/2}, F = 1 \leftrightarrow 5^2P_{3/2}, F = 2$, is divided into two beams. One beam (repumping 1) participates in the laser-cooling process and the other beam (repumping 2) enforces the labeling of the atoms along the central axis. The cooling light, optical pumping light, and repumping 1 light combine into one beam, and then form a parallel hollow beam with diameter of 34 mm and width of 1 mm via a pair of axicons. Eventually, the hollow beam is injected into the cylindrical cavity and is diffusely reflected inside the cavity. The repumping 2 light and probe light propagate vertically along the central axis through the cavity, with Gaussian beam diameters of 0.96 and 2.63 mm, respectively.

Our labeling process is accomplished by our distinguishing the two hyperfine ground levels. After interaction with

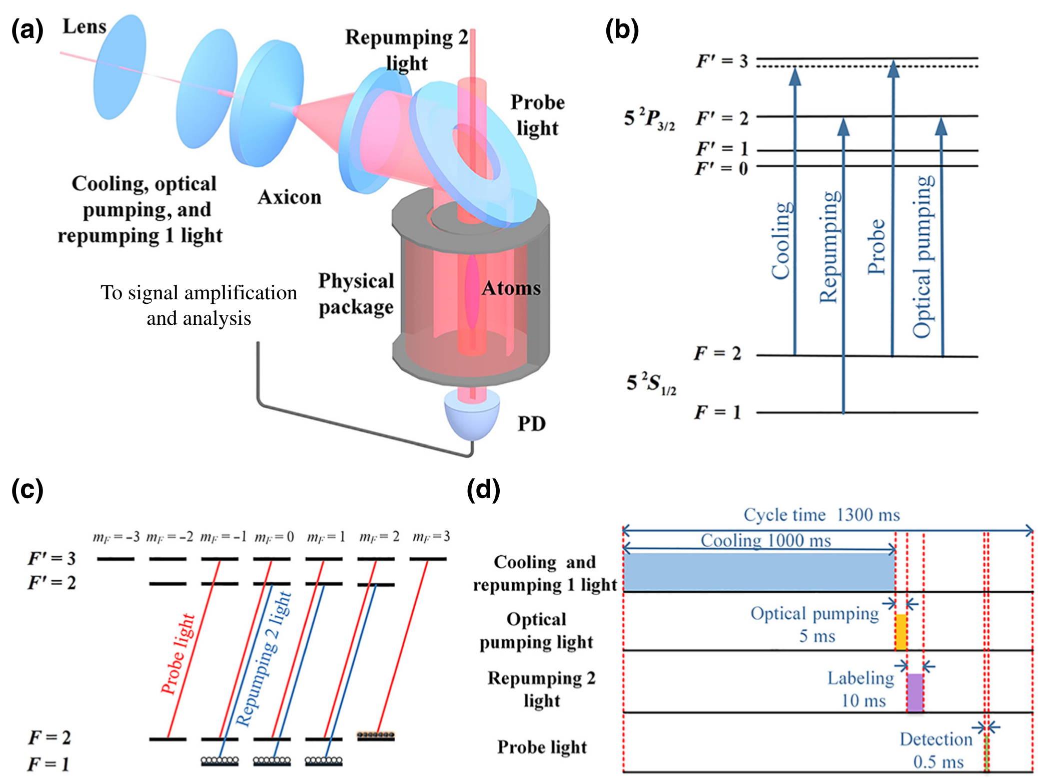

FIG. 1. (a) The experimental setup. The cylindrical cavity is mounted vertically and the cold-atom ensemble has a long-cigar shape. The optical detection axis is along the central axis of the cylindrical cavity. The probe light propagates through the cold atoms and arrives at a photodetector (PD). (b) Relevant energy levels and transitions of the ^{87}Rb D2 line for our experiment. (c) Details of the Zeeman substates and relevant polarization degrees of freedom for the nearly-nondestructive-detection method. (d) A sample time sequence for the basic destructive-type detection process. Firstly, atoms are cooled down via ILC. Secondly, optical pumping light transfers all intracavity cold atoms to the level of $5^2S_{1/2}$, $F = 1$. Afterward, repumping 2 light populates the atoms to $5^2S_{1/2}$, $F = 2$, along the central axis. Finally, during the detection stage, probe light is applied with a variable delay time that can be scanned.

optical pumping light and repumping 2 light, the cold atoms along central axis are pumped to $F = 2$, while the rest of the intracavity cold atoms stay in $F = 1$. Such an arrangement does not involve the polarization degree of freedoms. Here, the target segment is naturally chosen as the cold atoms along the central axis, exactly those we care about in typical applications of the ILC platform. The labeled atoms will subsequently start the diffusion process: namely, expanding freely due to their thermal motions. Monitoring the diffusion process over time will yield the temperature information.

To begin with, we demonstrate the general case with a destructive-type detection process, and Fig. 2 shows the outcome of such a measurement. For simplicity, we ignore the finite width of the labeled-atom ensemble, and effectively treat it as a thin line [37]. Then after diffusion, the labeled atoms' spatial-density profile at a later time directly reflects their original velocity distribution at the beginning. Because the time duration of diffusion is relatively short and the direction of gravity is along the central axis, the effects of gravity can also be virtually dismissed for now. With respect to the geometry of this system, the dynamics in the dimension along the central axis does not have a significant impact on the outcome, and therefore it suffices to consider the process in a two-dimensional setting in the transverse plane. In laser cooling, assigning the temperature to a cold-atom ensemble requires careful clarification, since the ensemble does not necessarily sit in a thermal-equilibrium state. For our case, the justification comes from the information from the velocity-distribution profile, which can be deduced from analysis of the experimental data. It is well described by the two-dimensional Maxwell-Boltzmann distribution $f(v)dv = (m/2\pi k_BT)2\pi v \exp(-mv^2/2k_BT)dv$. According to the equipartition theorem, the temperature in three dimensions T_{3D} can be deduced as $T_{3D} = T_{2D} \times 3/2$, where T_{2D} is the temperature in two dimensions, by the inherent isotropic property of ILC in the kinematics of each dimension.

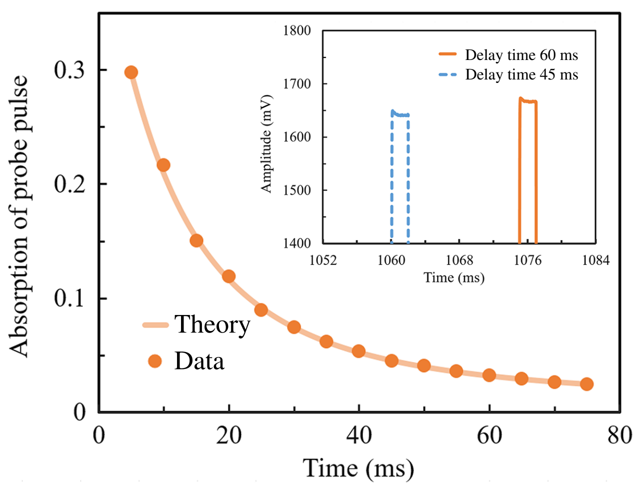

FIG. 2. A typical result with each data point taken in a new cycle of the experiment. The cooling-laser power is 120 mW and the cooling time is 1000 ms. The inset shows the raw data of amplified voltage signals from probe-pulse incidences on the photodetector, time stamped with respect to a standard experimental cycle. The error bar is smaller than the data dot size and therefore is omitted. The theoretical curve according to Eq. (2) is shown, and the temperature is deduced to be 41.9 ± 2.6 μK with the factor of 3/2 already included.

Basically, our method is linked with counting the number of labeled atoms within a prescribed confined region. Hotter samples tend to diffuse faster with fewer residual atoms, and vice versa. After time delay t, the number of atoms remaining in the region with radius r_c is proportional to [37]

$$s(r_c, t) = 1 - \exp\left(-\frac{m(r_c/t)^2}{2k_BT}\right). \tag{1}$$

Scattering off these atoms will lead to a reduction in the transmission of the probe-laser pulse. In typical methods such as absorption imaging [39,40], the temperature information can be deduced from the change in the density profile. On the other hand, in our method the signal is registered via a single photodetector based on the overall absorption, or very loosely speaking, the integration of density with weights imposed by the probe-laser spatial profile, rather than the images of the detailed density profile. Such a procedure has similarities and connections with optical imaging via compressive sampling techniques [41–44], and the photodetector is effectively a single-pixel bucket detector, which provides adequate temperature information from the density-profile change of the labeled cold atoms [37,40]. Under the assumption that the cold atomic gas is relatively dilute and the delay time is not too short, the reduction of the probe-pulse transmission signal is proportional to

$$\left(\frac{2}{(d/2t)^2} + \frac{m}{2k_BT}\right)^{-1}, \tag{2}$$

where d is the Gaussian diameter of the probe light [37].

Typical cold-atom temperature-measurement techniques such as the TOF method or imaging after release are a type of destructive detection. On the other hand, evaluation of temperature via nondestructive measurement has been of essential interest in the field, and such methods have already been discussed [23]. The basic experiment for Fig. 2 is also destructive in the sense that interaction with the probe pulse changes the internal quantum state of cold atoms and the original labeling does not persist. Hence, a complete measurement trace requires repeated trials of replenished cold atoms. However, if we include the polarization degrees of freedom in the system, a nearly-nondestructive-type method can be constructed with the

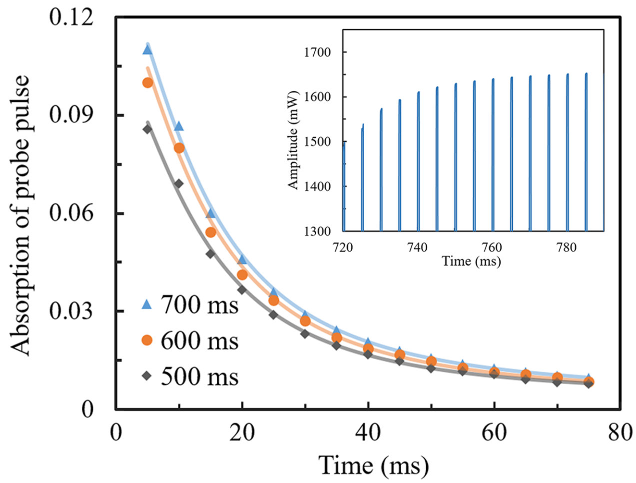

FIG. 3. Results of temperature measurement by the nearly-nondestructive-type method for cold atoms with different cooling times under ILC. The cooling-laser power is set at 60 mW. The differences in absorption amplitudes between these curves are mostly due to the differences in the numbers of accumulated cold atoms, which depend on the cooling time. The inset shows a sequence of raw data in terms of the amplified probe-light signal, all taken consecutively in the same experimental cycle.

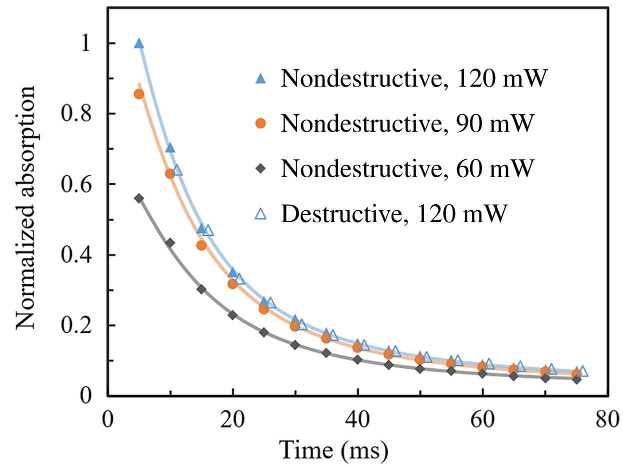

FIG. 4. Temperature measurement with respect to different cooling-laser powers via nearly nondestructive measurement plotted in terms of normalized absorption of the probe pulse at different delay times. A comparison between destructive-type and nondestructive-type methods is also included. All nondestructive-type-measurement data points are normalized with the same standard, while the destructive-type counterparts are normalized differently for better visualization of the comparison. The cooling time is set as 1000 ms.

help of the cycling transition, as in the case of atomic qubit readout [45–49].

More specifically, for ^{87}Rb, an appropriate cycling transition can be chosen as $5S_{1/2}|F=2, m_F=2\rangle \leftrightarrow 5P_{3/2}|F=3, m_F=3\rangle$, as shown in Fig. 1(c). Accordingly, we introduce necessary changes into the labeling process such that the labeled atoms are sent to $|F=2, m_F=2\rangle$, while the rest of the atoms stay in $F=1$ [37]. Then, interaction of a weak probe pulse of right circular polarization will not destroy the prescribed labeling, and nearly nondestructive detection of the temperature can be realized. A magnetic bias field is not necessary for this. In particular, a complicated interferometer design or a delicate imaging setup is not requited.

Then we implement this type of nearly nondestructive method and we investigate the influence of the cooling time on the temperature, as shown in Fig. 3. According to curve fitting via Eq. (2), the temperature difference in these three cases is within approximately 0.5 μK. Such a test confirms that as long as the cooling time is not too short, it does not have an effect on the ultimate temperature of cold atoms in ILC.

III. FURTHER INVESTIGATIONS

Next we investigate the influence of the cooling-laser power on the temperature; the results are shown in Fig. 4. We also include a direct comparison between the nearly-nondestructive-type measurements and the destructive-type measurements. This sample data yield identical temperatures in both cases, which verifies the feasibility of the nondestructive-type method. In principle, one main limiting factor comes from the heating of the cold atoms caused by the scattering of the probe light, and this requires us to maintain a relatively low power setting. For our experiment the probe-light power is kept at less than 1 μW.

As an advantage of the nondestructive method, a complete measurement trace can be accomplished in one experimental cycle without the internal state of the labeled atoms being changed. For the purpose of adequately discussing the characteristics of this method, so far we have chosen to present data with an extended time duration. On the other hand, for practical applications, it is preferred that the temperature of the cold-atom ensemble can be assessed in the first few milliseconds or even sooner, while the majority of the atoms' internal states are kept unperturbed, ready for the next phase of experiments [37]. Obtaining the temperature relatively fast is another feature of our method, and we show such an example in Fig. 5. A shorter probe pulse and a greater signal-to-noise ratio can further reduce the time cost to obtain the temperature.

IV. SUB-DOPPLER COOLING OF ILC

As stated earlier, we choose the form of a hollow beam in order to feed the cooling-laser light into the cylindrical cavity for ILC. This recently proposed design is an update based on our previous studies [30,32,38], with the aim of generating a more-uniform intracavity diffuse optical field and increasing the concentration of atoms along the central axis. While the performance in general exhibits an obvious

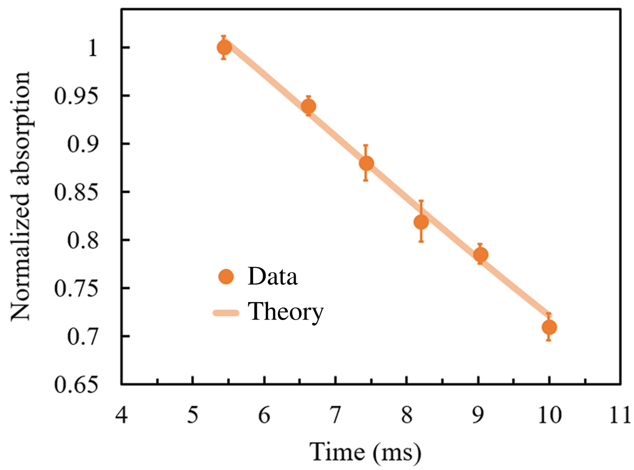

FIG. 5. A sample measurement result with reduced time cost. The cooling-laser power is 129 mW and the cooling time is 1000 ms. The temperature is $45.0 \pm 2.5\ \mu$K according to the theoretical fitting. The time cost of only the detection process is on the order of approximately 5 ms.

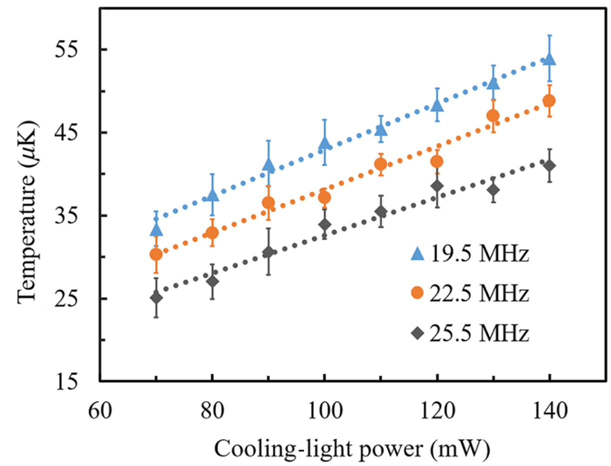

FIG. 6. Relation between the cooling-laser power $\mathcal{I}$ and the cold-atom temperature T in ILC for selected cooling-laser detunings. Linear curve fitting is shown, where the intercepts on the temperature axis are at around 10 μK [37]. The cooling time is set to 1000 ms for all cases. This constitutes an analogy to measurements of temperature scaling laws in optical molasses [52] and MOT [53].

improvement, we observe that the measured temperatures seem to be consistently much lower than the Doppler temperature $T_D \approx 145.6\ \mu$K of ^{87}Rb. The phenomenon of sub-Doppler cooling has been extensively observed in ILC experiments of various instantiation forms, although there are still some puzzles regarding the fundamental mechanisms. For instance, Ref. [31] proposes that the underlying principle can be explained as Sisyphus cooling in a speckle laser field [50,51].

Following the observation of the influence of the cooling-laser power, we perform further investigations into the relation between temperature and cooling-laser power, and a typical result is shown in Fig. 6. It provides insight into the physics of the temperature scaling law of ILC, and in particular it hints at the embedded sub-Doppler-cooling properties.

We may deduce the simplified one-dimensional form of the sub-Doppler-cooling force profile in terms of $F = -\beta_{\text{sub}}(\delta)v$ from elementary analysis based on Fig. 6, with δ being the cooling-laser detuning. More specifically, under the framework of the Fokker-Planck equation to interpret laser cooling, the temperature limit of $k_B T = mv^2/2$ is achieved when the magnitudes of the cooling rate $F \cdot v$ and the heating rate $4\hbar\omega_r\gamma_p$ are equal, with ω_r being the recoil frequency $\omega_r = \hbar k^2/(2m)$ and γ_p being the effective scattering rate. On basis of the apparently linear relation in Fig. 6, we can ignore the relatively small term of intercepts and treat the relation as $T = \eta(\delta) \times \mathcal{I}$. By definition, the saturation parameter is proportional to intensity $s_0 = \alpha\mathcal{I}$, and we have the approximate relation at low intensity: $\gamma_p \approx s_0\gamma[1 + (2\delta/\gamma)^2]^{-1}/2$, with γ being the natural line width. Then eventually we arrive at the following equation as the one-dimensional description:

$$|F(\delta)| \approx \frac{1}{2}\frac{\alpha}{k_B\eta(\delta)}\frac{\hbar^2k^2\gamma}{1 + (2\delta/\gamma)^2}|v|. \tag{3}$$

Therefore, the information regarding β_{sub} can be extracted according to $\eta(\delta)$ from the linear fittings in Fig. 6 and the experimentally measured value of α. Staying with the one-dimensional description, we find the ratio α is on the order of approximately 0.01 per milliwatt for our system. According to Eq. (3), from the collected data we can estimate that $|\beta_{\text{sub}}/\beta_{\text{OM}}| \gg 1$, where β_{OM} is the damping coefficient of a typical Doppler-cooling process in one-dimensional optical molasses [54].

Among many potential applications of this method, we note two particular examples: cold atoms in space missions and ultracold atoms such as a BEC. Quantum technologies based on cold atoms in space missions have become a focus in the research community recently [17,55,56]. Several characteristics of our method appear attractive for this purpose: the basic principles fit the scenario of microgravity, the detection process is relatively fast, and the apparatus is suitable for integration into a compact system. Nondestructive thermometry of ultracold atoms, especially a BEC, has constantly attracted much interest. We hope that our method will be helpful in this direction as well. One of the delicate points is that the heating effect must be kept at a very low level throughout the entire process [40]. For typical alkali atoms, while the labeling process between the two hyperfine ground states can be driven by a Raman transition to avoid heating, the probe light has to be kept at an appropriately low power level to maintain a small number of overall scattered photons. Moreover, we will also explore potential possibilities of extending our results with respect to the emerging topic of quantum thermometry [57] in future work.

V. CONCLUSION AND OUTLOOK

In conclusion, we design, realize, and characterize a nearly nondestructive method to measure the temperature of a labeled segment of cold atoms, together with a careful experimental investigation of its applications to ILC. It is realized via a proper cycling transition enforced by use of the polarization degrees of freedom and a bucket detector. This method is straightforward to implement and can yield temperature information in several milliseconds. It has a unique feature to address the atoms along the optical detection axis, which is of essential value to ILC and other cold-atom platforms commonly used in quantum metrology and quantum sensing. Moreover, with the help of this method, we systematically study the influence of cooling-laser parameters on the resulting cold-atom temperature of ILC. In particular, we investigate the sub-Doppler-cooling properties of ILC by studying the relation between temperature and cooling-laser power.

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