

Λ -Enhanced Gray-Molasses Loading and EIT Cooling of Neutral Atoms in Nanophotonic Traps

Lucas Pache^{✉,*}, Antoine Glicenstein^{✉,†}, Philipp Schneeweiss[✉], Jürgen Volz[✉],
Arno Rauschenbeutel^{✉,‡} and Riccardo Pennetta[✉]

Department of Physics, Humboldt-Universität zu Berlin, 10099, Berlin, Germany



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Nanophotonic traps for cold atoms typically have trap volumes that are orders of magnitude smaller than, e.g., free-space optical tweezers. This makes efficient loading of these traps challenging, thereby limiting the total number of atoms coupled to the nanophotonic waveguide. Here, we demonstrate that Λ -enhanced gray-molasses (Λ GM) can substantially increase the number of trapped atoms in a nanofiber-based cold-atom setup. Specifically, we observe a sixfold increase in the number of loaded atoms compared to conventional red-detuned polarization-gradient cooling. Despite the unusually small depth of our optical trap of only 24 μ K, we load about 4000 individual cesium atoms, achieving optical depths exceeding 140 and reaching the collisional blockade regime over a length of approximately 1 mm. After loading, we perform efficient electromagnetically induced transparency (EIT)-assisted cooling that is found to increase the trap storage time to 400(9) ms. This is a fivefold improvement over the passive storage time. Remarkably, we observe that EIT-cooling also works with two co-propagating nanofiber-guided light fields and requires only a few hundred picowatts of optical power. Our results provide an efficient method to boost both the number of loaded atoms and the storage time of nanophotonic atom traps.

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I. INTRODUCTION

Interfacing trapped neutral atoms with nanophotonic waveguides enables the experimental observation of stable and efficient interactions between guided photons and ensembles of up to thousands of atoms [1–4]. In the last decade, this capability has enabled significant advances in, e.g., quantum optics [5–11], quantum information processing [12–19], and studies of collective radiative phenomena [6,20–23]. These achievements have been made possible by the development of a wide range of nanophotonic platforms for cold-atom experiments, including optical nanofibers [24,25], slow-light waveguides [26], whispering-gallery-mode resonators [15,18,27,28], and photonic crystal cavities [29,30].

In all these different platforms, atoms are typically trapped either by optical potentials formed by guided modes [24] or by external optical tweezers, which are

partially reflected by the waveguide [29]. Both approaches share a defining feature: the trapping potentials occupy much smaller volumes compared to conventional atom traps in free space. Specifically, typical volumes for nanophotonic traps are a few orders of magnitude smaller than λ^3 [1]. This renders the loading from a thermal cloud of laser-cooled atoms challenging. As a consequence, efficient and reliable controlled atom loading remains a central challenge in this field.

Recently, Λ -enhanced gray molasses (Λ GM) cooling [31–35] has emerged as a highly effective technique for achieving high loading efficiencies in optical dipole traps for neutral atoms [36–38]. By combining velocity-selective coherent population trapping with polarization-gradient cooling in a blue-detuned configuration, Λ GM realizes sub-Doppler cooling while strongly suppressing photon scattering, yielding temperatures on the order of 1 μ K for cesium atom clouds [32].

In this work, we experimentally demonstrate that Λ GM and the closely related technique of electromagnetically induced transparency (EIT) cooling [39–43] can address several of the challenges posed by nanophotonic interfaces for laser-cooled atoms. Specifically, we show that Λ GM can substantially enhance the loading of nanofiber-based traps for cold atoms. In our experiment, we observe a sixfold increase in the number of trapped atoms compared to loading with red-detuned polarization-gradient cooling (RPGC). This enables the trapping of about 4000 individual atoms and reaching maximum occupation in the

*Contact author: pachluca@hu-berlin.de

[†]Present address: LP2N, Laboratoire Photonique, Numérique et Nanosciences, Université de Bordeaux-IOGS-CNRS: UMR 5298, F-33400 Talence, France.

[‡]Contact author: arno.rauschenbeutel@hu-berlin.de

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collisional blockade regime [44]. Using the same optical beams employed for Λ GM, we implement EIT-assisted cooling of the atoms trapped near the nanofiber. This is particularly noteworthy because our experiment uses very shallow traps with a trap depth of only 24 μ K, for which standard RPGC was found to be ineffective. This approach not only yields a fivefold increase in the atom storage time, but also allows us to preserve the comparatively high atom-photon interaction strength observed immediately after loading over very long storage times. Finally, we demonstrate that EIT-cooling can also be implemented by exclusively using guided beams with a total power of just a few hundred pW.

II. EXPERIMENTAL SETUP

The experimental setup is shown schematically in Fig. 1(a). We interface an ensemble of laser-cooled cesium atoms with the evanescent field of light propagating in an optical nanofiber with a nominal radius of 225 nm. The nanofiber is realized as the waist of a tapered optical fiber.

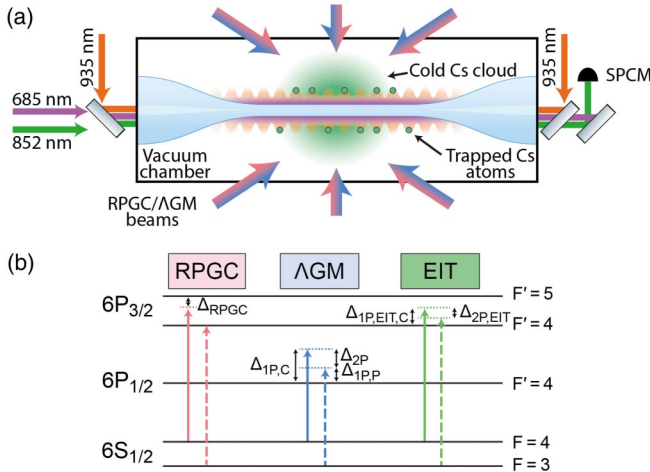


FIG. 1. (a) Experimental setup for our nanofiber-based cold-atom interface. We prepare a cloud of cold cesium atoms close to a 225-nm-waist-radius nanofiber by using a 3D-MOT and molasses configuration with σ^+ and σ^- polarization of the counter-propagating light fields. We trap the atoms close to the surface of the nanofiber using a fiber-guided red-detuned light field ($\lambda_{\text{red}} = 935$ nm) in a standing wave configuration and a fiber-guided blue-detuned light field ($\lambda_{\text{blue}} = 685$ nm) in a running wave configuration. We use fiber-guided light fields on the D2 transition ($\lambda_{\text{green}} = 852$ nm) to probe the atoms and to perform EIT-cooling. The probe light is detected using a single-photon counting module (SPCM). (b) Energy level scheme of the transitions used for molasses cooling. The RPGC-molasses is performed on the D2 cycling transition. The Λ GM-cooling is performed on the D1-transition. Specifically, the main cooler light field and the phase-coherent second light field couple the two hyperfine ground states to form a Λ -system via the $F' = 4$ hyperfine excited state. The Λ -system to conduct EIT-cooling is realized on the D2 line via the $F' = 4$ hyperfine excited state.

The atoms are trapped in the evanescent field of the nanofiber using a two-color dipole trap [24]. In our experiment, the red- and blue-detuned trapping light fields operate at wavelengths of $\lambda_{\text{red}} = 935$ nm and $\lambda_{\text{blue}} = 685$ nm, which is close to magic wavelengths of the D2-transition [25,45]. For all results in this paper, the red-detuned trapping field is set to a power of $P_{\text{red}} = 55$ μ W and is launched from both ends of the nanofiber to create a standing-wave dipole trap. The blue-detuned beam has a power of $P_{\text{blue}} = 7.75$ mW. This configuration results in traps with a calculated depth of 24 μ K with a minimum located about 270 nm from the nanofiber surface [46]. Due to their small trapping volumes of about 1×10^{-16} cm³, the nanofiber traps have an occupancy of at most one atom per trapping site in the collisional blockade regime [24,44].

The experiment begins by preparing a cloud of laser-cooled atoms in a magneto-optical trap. We then proceed with an initial stage of RPGC on the D2 transition [see Fig. 1(b)], yielding a cloud temperature of 5.5 ± 0.2 μ K, determined using a time-of-flight measurement. Subsequently, we implement Λ GM cooling [32,33]. In this stage, two phase-coherent lasers, which we refer to as control and probe beams respectively, are applied in a Λ configuration on the D1 transition, coupling the two hyperfine ground states to the $6P_{1/2}$, $F' = 4$ excited state. The control beam is blue-detuned by $\Delta_{1P,C} = 4.5 \Gamma_{D1}$ from the $F = 4 \rightarrow F' = 4$ transition, while the detuning of the probe beam is denoted as $\Delta_{1P,P}$. The two-photon detuning is defined as $\Delta_{2P} = \Delta_{1P,P} - \Delta_{1P,C}$ [see Fig. 1(b)], and it is experimentally controlled by varying $\Delta_{1P,P}$ [see Fig. 1(b)]. After 150 ms of Λ GM cooling, the atomic temperature was found to be 1.9 ± 0.1 μ K (see the Supplemental Material [47] for more details of experimental sequence and the Λ GM cooling scheme). We estimate the optical depth (OD) of the nanofiber-trapped ensemble by performing transmission spectroscopy through the nanofiber on the $F = 4 \rightarrow F' = 5$, D2 cycling transition. In addition, we estimate the total number of trapped atoms, N , using the technique described in Ref. [48]. This method consists of measuring the optical energy required to pump an ensemble initially prepared in the $F = 4$ ground state into the $F = 3$ ground state, using a laser resonant with the $F = 4 \rightarrow F' = 4$, D2 transition. With these two independent measurements, we can estimate the atom-photon coupling strength β , defined as the probability for an excited atom to decay by emitting a photon into the waveguide, as $\beta = \text{OD}/(4N)$. Immediately after loading, we measure $\beta = 1.08 \pm 0.03\%$.

III. LOADING OF NANOFIBER-BASED TRAP

We start by characterizing the loading dynamics of the nanofiber trap during the RPGC and Λ GM phases. Figure 2 shows the measured OD as a function of the duration of these two cooling stages, i.e., the loading time.

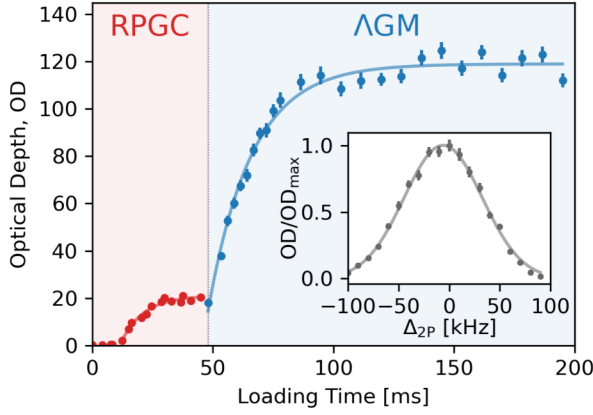


FIG. 2. Measurement of the OD of the trapped atomic ensemble for different loading times. During the red-shaded time interval, the atoms are loaded using the RPGC-molasses for up to 50.0 ms when they reach a steady state OD of 20.4 ± 1.2 . During the blue-shaded time interval, the atoms are loaded further using the Λ GM. During this second stage, we measure an increase in the OD by a factor of six with a maximum of 125 ± 4 . Lines: Exponential fits to the data. Inset: Measurement of the final OD normalized to the maximally measured OD for different two-photon detunings Δ_{2P} . The dependence is well described by a Gaussian distribution with a maximum close to the two-photon resonance (gray line).

During the RPGC, the OD remains approximately zero for the first 15 ms, which we attribute to the atoms being still too hot to be loaded into our comparatively shallow traps. After this initial period, the measured OD increases, saturating at $OD = 20.4 \pm 1.2$. The measured data are well described by a saturating exponential, in this case with a time constant of $\tau_{\text{RPGC}} = 9.4 \pm 1.6$ ms. After 45.0 ms, we switch off the RPGC beams and start the Λ GM phase. As shown by the blue data points in Fig. 2, a pronounced increase in the optical depth is observed, saturating at $OD = 125 \pm 4$. This corresponds to a sixfold enhancement of the OD compared to the RPGC phase alone. The data are again well described by a saturating exponential with a time constant of $\tau_{\Lambda\text{GM}} = 18.0 \pm 1.1$ ms. For a fixed current in the cesium dispensers, this sequence, combining RPGC and Λ GM, yields the highest OD. In particular, attempting to load the nanofiber trap using only Λ GM (i.e., without the initial RPGC stage) results in significantly lower OD. By increasing the cesium dispenser current, even larger OD can be obtained without any modifications to the experimental sequence (see Supplemental Material [47]). These measurements were performed at the experimentally found optimal two-photon detuning, $\Delta_{2P} = -5.9 \pm 0.6$ kHz, yielding the largest OD after loading by the Λ GM. This was determined by fitting a Gaussian to the data as shown in the inset of Fig. 2. As expected, the value of Δ_{2P} is very close to the two-photon resonance, confirming that optimal loading occurs when atoms are in the velocity-selective dark state of the Λ GM.

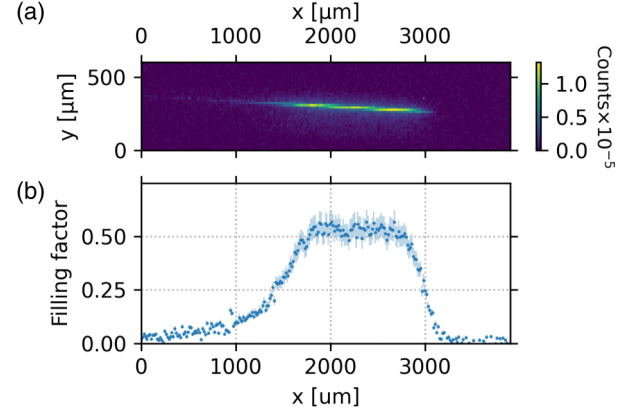


FIG. 3. (a) EMCCD-fluorescence image recorded while probing with the fiber-guided EIT cooling light fields (see Supplemental material [47]). We note that the apparent intensity modulation along the nanofiber axis arises from imperfect alignment of the camera pixel-lines with the nanofiber axis. (b) In conjunction with an independent atom number measurement, we determine the local filling factor of the trapped ensemble. We observe a flat-topped atom distribution with a maximum filling factor of about 50%, which indicates trap operation in the collisional blockade regime.

We attribute the observed offset from $\Delta_{2P} = 0$ to residual differential light shifts induced by the trapping light fields and possible residual magnetic fields.

As depicted in Fig. 2, we observe a saturation of the loaded OD when applying the Λ GM for loading durations exceeding 50 ms. To understand this observation, we proceed by estimating the filling factor, i.e., the probability of finding a single atom in each trap site. This is performed by first measuring the total number of trapped atoms [48] and then estimating the line density of the trapped atoms along the nanofiber by imaging the atomic fluorescence using an electron-multiplying charge-coupled device (EMCCD) [49]. An image of the trapped atoms is shown in Fig. 3(a). With these two measurements at hand, we can calculate the filling factor, considering that the distance between two trap sites is given by $\lambda_{\text{red}}/(2n_{\text{eff}}) = 434$ nm, where $n_{\text{eff}} = 1.08$ is the effective refractive index of the optical mode. Furthermore, there are two arrays of trapping sites that are diametrically opposed to each other. One array is located above the nanofiber, and the other is located below it, as depicted Fig. 1(a). As apparent from Fig. 3(b), we observe a roughly constant line density of the trapped atoms over a region of 1 mm with a filling factor for each trapping site of about 50%, i.e., the maximum allowed in the collisional blockade regime [44]. Beyond this point, no further increase in the number of loaded single atoms occurs in the center of our ensemble. Thus, in order to reach an even larger OD, the size of the atomic cloud would have to be increased. This result is further substantiated by measuring the traps' atom loading and loss rates, as detailed in the Supplemental Material [47].

We note that on the right-hand side in Fig. 3, the up-tapered region of the tapered optical fiber begins. There, the intensities of the evanescent fields rapidly decrease and stable trapping is no longer possible. We note that it has been reported previously that the collisional blockade regime has been reached in a nanofiber cold-atom setup solely based on the shape of the atomic fluorescence signal [50], but the number of trapped atoms and consequently the filling factor was not measured.

IV. COOLING OF TRAPPED ATOMS

We now investigate the effect of the Λ GM light fields on the atoms that are already stored in the nanofiber trap. Because the atoms are spatially confined, the Λ GM beams are expected to induce not only polarization-gradient cooling but also EIT-cooling [39,51]. This additional cooling mechanism exploits the strongly asymmetric Fano-like absorption profile that can be realized in a Λ -type scheme when the control beam is far-detuned with respect to the atomic resonance. In the following, we define the two-photon detuning $\Delta_{2P,EIT}$ as zero, when the probe and control light fields resonantly couple the hyperfine ground states with the same motional quantum number. In this case, the ensemble becomes transparent for the probe field for transitions that do not change the motional state of the atoms, while the probe field is most absorbed for the transitions in which one quantum of motion is removed from the system.

We begin our investigation of the cooling mechanism by measuring the passive storage time of the atoms in the nanofiber traps. To do so, we turn off all molasses beams after loading and then measure the OD as a function of the holding time in the trap as depicted in Fig. 4(a). By fitting an exponential decay to our data, we determine a storage time of $\tau_p = 79 \pm 2$ ms. We then repeat this experiment, but after a certain delay we turn the Λ GM laser beams on again. To apply Λ GM-cooling exclusively on atoms in the nanofiber trap and avoid reloading of empty trap sites, this delay time must be long enough for the cloud of surrounding, non-trapped atoms to drop sufficiently below the nanofiber. In our setup, this takes about 20 ms. Figure 4(a) shows the results for the cooling delayed by 45 and 175 ms (red and orange data points, respectively). Interestingly, we observe that in both cases, right after turning on the cooling beams, the OD first increases on a timescale of a few tens of ms and then decays with a time constant of $\tau_a = 400 \pm 9$ ms. The latter is a fivefold increase with respect to the passive case. We note that in our comparatively shallow traps, we have not succeeded in increasing the storage time of the trapped atoms using RPGC.

To interpret these results, we measure the coupling strength, β , as a function of the holding time in the nanofiber trap with and without the Λ GM cooling light as seen in Fig. 4(b). For a non-cooled atomic ensemble (purple dots), we observe a steady decrease of β over time.

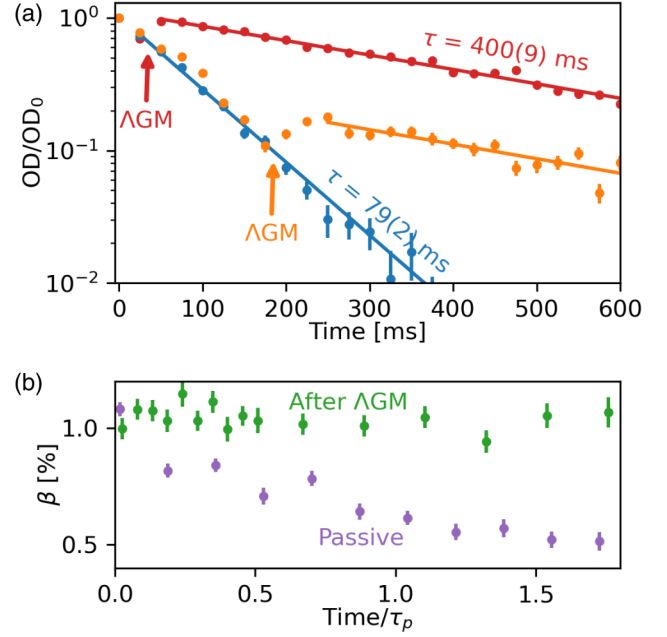


FIG. 4. (a) Measurement of the storage time of the trapped atoms after loading: The blue curve shows a measurement of the passive storage time of $\tau_p = 79 \pm 2$ ms of the atoms in the nanofiber-guided dipole trap. The red curve shows the storage time of $\tau_a = 400 \pm 9$ ms when the atoms are cooled by the Λ GM after 45 ms of delay. For the orange curve, the Λ GM-cooling light fields are switched on after a delay of 175 ms. (b) Measurement of the atom-light coupling strength β for different holding times normalized by the passive storage time τ_p : For a non-cooled atomic ensemble (purple) β decreases due to heating of the atoms. When applying the Λ GM-cooling light fields (green) the atom-light coupling strength is constant with its initial value of $\beta \approx 1\%$.

We attribute this phenomenon to heating of the atoms in the traps, which changes the spread of the atoms' distances and hence the average coupling between the atoms and the nanofiber [52]. Instead, when performing Λ GM-cooling during the holding time (green dots), no change in β is observed, indicating that in this case the atoms remain at the same temperature as right after the loading.

V. FIBER-GUIDED EIT-COOLING

In our nanofiber-based trap, atom loss is ultimately caused by heating in the radial direction. Interestingly, the radially decaying intensity profile of the evanescent guided light field enables the detection of the radial motional sidebands of nanofiber-trapped atoms [53]. This suggests that direct cooling of the radial motional degree of freedom using exclusively nanofiber-guided light should be possible. This is in contrast to conventional cooling schemes based on collimated or weakly focused light fields, where laser cooling along directions orthogonal to the propagation direction is typically prohibitively inefficient.

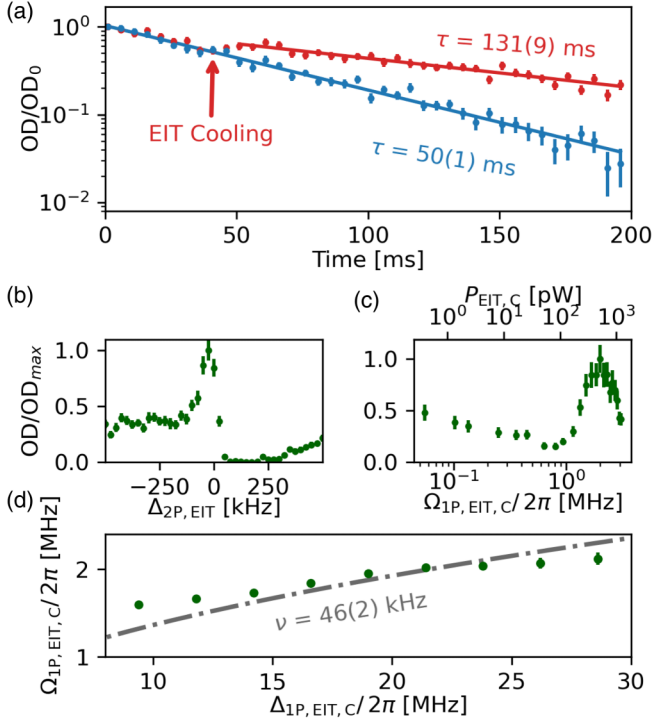


FIG. 5. (a) Measurement of the storage time of the trapped atoms after loading when applying no-cooling (blue) and the EIT-cooling light fields through the fiber (red). The blue curve is an exponential fit that yields a passive storage time of $\tau_p = 50 \pm 1$ ms of the atoms in the nanofiber-guided dipole trap. The red curve yields a storage time of $\tau_a = 131 \pm 9$ ms when the atoms are cooled with the fiber-guided EIT-cooling light. (b) We observe a Fano-type resonance in OD after a cooling duration of 20 ms when the EIT light fields are scanned across the two-photon resonance $\Delta_{2P,EIT}$. (c) We find the maximum OD for a power of the EIT-cooler light field of about 500 pW. (d) By repeating this measurement for a range of one-photon detunings, $\Delta_{1P,EIT,C}$, we determine the optimal $\Omega_{1P,EIT,C}$. We note that the error bars indicating the statistical uncertainty of the Rabi frequencies are smaller than the markers. A fit of the data yields a trap frequency of $\nu = 46 \pm 2$ kHz, see gray dash-dotted line.

To test cooling with guided light fields, we establish a Λ -system on the D2 transition, as depicted in Fig. 1(b), by introducing two additional phase-coherent guided light fields that co-propagate through the nanofiber. Figure 5(a) shows the measured storage time with and without the presence of the EIT-cooling via guided beams for a one-photon detuning of the strong control laser, $\Delta_{1P,EIT,C} = 2.5\Gamma_{D2}$. Again, two effects are visible: first, the storage time of the atoms in the trap is extended by a factor 2.6 and, second, a slight increase in the measured OD is observed when the cooling beams are switched on. This suggests that EIT-cooling via guided beams is also able to recover the initial value of the coupling strength, β , by cooling the atoms within the traps.

To better understand the cooling mechanism in this case, we show in Fig. 5(b), a measurement of the OD after a

cooling time of 20 ms for different two-photon detunings $\Delta_{2P,EIT}$. The result shows the Fano resonance characteristic of the EIT-cooling process, in which negative values of $\Delta_{2P,EIT}$ result in cooling, while positive values result in heating. We find that the maximum OD is obtained for $\Delta_{2P,EIT}$ around -25 kHz, i.e., very close to two-photon resonance.

The maximum cooling rate is expected when the absorption feature of the Fano resonance has a maximum at a two-photon detuning, $\Delta_{2P,EIT}$, equal to the trap frequency, ν . This occurs when the one-photon detuning, $\Delta_{1P,EIT,C}$, and the Rabi frequency of the control beam, $\Omega_{1P,EIT,C}$, satisfy the relation [39]:

$$\frac{1}{2} \left(\sqrt{\Delta_{1P,EIT,C}^2 + \Omega_{1P,EIT,C}^2} - |\Delta_{1P,EIT,C}| \right) = 2\pi\nu. \quad (1)$$

We investigate this condition by measuring the obtained OD after the application of EIT cooling when changing the Rabi frequency of the control beam, $\Omega_{1P,EIT,C}$. As depicted in Fig. 5(c), for $\Delta_{1P,EIT,C} = 2.5\Gamma_{D2}$ we observe a maximum of the OD for a power of the EIT-cooler light field of 500 pW. We repeat this measurement for different values of $\Delta_{1P,EIT,C}$ and determine $\Omega_{1P,EIT,C}$ at the maximum OD, as depicted by the green dots in Fig. 5(d). We find that our data fit the prediction of Eq. (1) for a trap frequency of 46 ± 2 kHz. For comparison, the calculated trap frequencies in our experiment are 55 kHz in the radial, 32 kHz in the azimuthal and 81 kHz in the axial direction.

According to Refs. [39,54], the overall rate of EIT cooling is determined by how rapidly the dark state changes as the atom moves or, more quantitatively, by the position-dependence of the ratio between the Rabi frequencies of the control and probe field, $\Omega_{1P,EIT,C}/\Omega_{1P,EIT,P}$. This means that for our co-propagating EIT cooling fields, the axial motion does not experience significant cooling. Also, the azimuthal degree of freedom is not cooled as the dark state is, to first order, independent of the azimuthal motion. This argument also applies for the radial direction as $\Omega_{1P,EIT,C}$ and $\Omega_{1P,EIT,P}$ decay exponentially, yet their ratio stays almost constant. However, our system exhibits an additional effect: a position-dependent light shift of the $F = 4$ ground state caused by off-resonant coupling to the $F' = 5$ excited state via the control EIT beam. First, this results in a position-dependent two-photon detuning. Second, it makes the standard two-color trapping potential state-dependent, meaning the trapping potentials of the $|F = 3\rangle$ and $|F = 4\rangle$ ground states shift slightly radially with respect to each other. In conjunction with the asymmetric EIT spectrum [39,54], the atom preferentially scatters light at a radial position where potential energy is removed from the atom. The maximum cooling efficiency of this process is expected when Eq. (1) is satisfied for the radial trap frequency. From a practical stand point, this

mechanism is useful because it is easy to implement co-propagating beams experimentally.

VI. CONCLUSIONS

In conclusion, our results establish AGM and related cooling techniques as important tools for nanophotonic interfaces with laser-cooled atoms. We demonstrate that these methods can substantially enhance the loading of nanophotonic traps, reaching filling factors that are currently limited by collisional blockade. Importantly, since AGM operates with blue-detuned light, it could in principle be used to achieve filling factors beyond the collisional blockade limit via tuned light-assisted collisions [34,37]. For this reason, implementing AGM in nanophotonic cold-atom interfaces could prove crucial for investigating collective radiative phenomena that require high filling factors, such as selective radiance [49,55]. This regime, however, was not explored in the present work. In fact, this would require the trap depth $U \gtrsim \hbar\Gamma_{D1}$ [37], i.e., about one order of magnitude larger than explored here.

All of our results have been obtained in comparatively shallow trapping potentials requiring minimal optical power. This is an important advantage for integrated nanophotonic platforms, where optical absorption and heat dissipation impose critical constraints. In this context, we also demonstrate that efficient EIT-cooling using exclusively fiber-guided beams requires power as low as a few hundred pW. Looking ahead, it would be highly desirable to extend the demonstrated techniques, e.g., for directly loading atoms into nanophotonic traps, without the need for externally applied cooling laser beams.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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