

Polarization-insensitive state preparation for trapped-ion hyperfine qubitsA. D. Leu¹,* M. C. Smith¹,* M. F. Gely¹,* and D. M. Lucas*Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*

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Quantum state preparation for trapped-ion qubits often relies on high-quality circularly polarized light, which may be difficult to achieve with chip-based integrated optics technology. We propose and implement a hybrid optical and microwave scheme for intermediate-field hyperfine qubits which instead relies on frequency selectivity. Experimentally, we achieve 99.94% fidelity for linearly polarized (σ^+/σ^-) light, using $^{43}\text{Ca}^+$ at 28.8 mT. We find that the fidelity remains above 99.8% for a mixture of all polarizations ($\sigma^+/\sigma^-/\pi$). We calculate that the method is capable of 99.99% fidelity in $^{43}\text{Ca}^+$, and even higher fidelities in heavier ions such as $^{137}\text{Ba}^+$.

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Trapped ions are one of the foremost experimental platforms for quantum computation [1], demonstrating leading error figures for single-qubit gates [2,3] and entangling gates [4,5]. Ions also make excellent quantum memories, especially isotopes with nuclear spin, which feature “clock” qubit transitions with coherence times that can exceed an hour [6,7]. Using clock qubits comes however at the cost of a dense hyperfine level structure, complicating motional cooling and qubit state preparation and measurement (SPAM) [8–12]. This is particularly true for isotopes with nuclear spin $I > 1/2$, for example the commonly used $^9\text{Be}^+$ [13], $^{25}\text{Mg}^+$ [4,14], $^{43}\text{Ca}^+$ [2,11], or $^{137}\text{Ba}^+$ ions [8]. In this Letter we focus on state preparation in such isotopes.

Optical pumping schemes [15] are required to prepare these isotopes into specific hyperfine states. For $I > 1/2$ isotopes, optical pumping typically relies on polarization selection rules to render one state dark to laser driving. The success of such an approach hinges on the high polarization purity of the optical pumping beam. However, this requirement constrains the beam delivery setup, and can complicate the use of on-chip integrated optics [16]. While integrated delivery of high-purity circularly [17] and linearly [18] polarized light has been demonstrated, it will introduce an additional degree of complexity when scaling quantum processors.

Recently, an alternative approach to state preparation of $I > 1/2$ isotopes has been demonstrated which does not solely rely on high-purity polarization [8]. In Ref. [8], optical pumping enables the preparation of a mixture of states within one hyperfine manifold, where the other manifold remains dark due to the frequency detuning arising from the hyperfine splitting. Coherent microwave or quadrupole laser pulses are then used to transfer all but one state back to the bright hyperfine

manifold for another round of optical pumping, and then the cycle is repeated. Avoiding leakage out of the prepared state imposes a minimum duration of the coherent pulses, and polarization-dependent optical pumping is thus used to reduce the total state-preparation duration. To eliminate the requirements on polarization altogether, without compromising on the state-preparation duration, one could introduce a larger Zeeman shift between the hyperfine levels to isolate the target state in frequency space. This could be achieved by using an “intermediate-field” clock qubit, such as the 14.6 or 28.8 mT clock transition in Ca^+ , or the 21.3 mT transition in Mg^+ . Regardless of state-preparation considerations, the advantages of intermediate-field qubits have been used to demonstrate some of the highest-performance logical gates, in particular using microwave (MW)-driven gates [2,4,13,14,19]. However, we find that the scheme of Ref. [8] is not effective at intermediate field. Indeed, with a Zeeman splitting exceeding the 397 nm dipole transition linewidth, an increased laser intensity is required to address multiple states within the hyperfine manifold. This larger laser intensity results in percent-level state-preparation errors by off-resonantly addressing the prepared state (see Supplemental Material Sec. S5 [20]), prompting the alternative scheme demonstrated in this Letter.

In this Letter, we present a frequency-selective state-preparation (FSSP) method relying on the large Zeeman shifts of “intermediate-field” $I > 1/2$ ions and their hyperfine splitting rather than laser polarization purity. We demonstrate state preparation of a qubit state in $838\mu\text{s}$ with a SPAM error of $1.2(1) \times 10^{-3}$ using linearly polarized light, and discuss the expected errors when FSSP is applied to other ion species. We compare this technique to an implementation of a polarization-selective state-preparation (PSSP) scheme. Using the PSSP scheme, we demonstrate an improvement on previous implementations [2], reaching a SPAM error of $4.7(4) \times 10^{-4}$ with a state-preparation duration of 1.2 ms. The two techniques are shown schematically in Fig. 1.

Experiments are carried out on a segmented-electrode surface trap with an on-chip MW resonator, described in Ref. [21]. Single $^{43}\text{Ca}^+$ ions are trapped at a $40\mu\text{m}$ height

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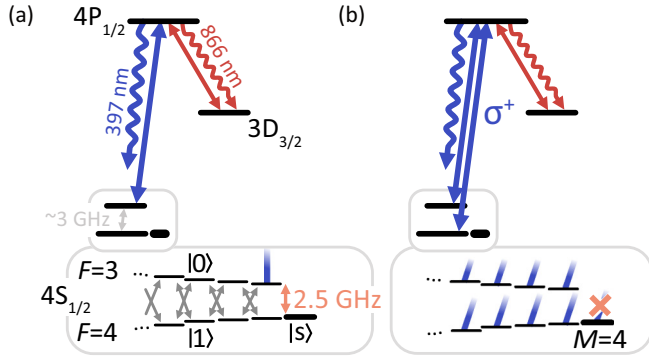


FIG. 1. Both panels show the energy levels of a $^{43}\text{Ca}^+$ ion at 28.8 mT and the transitions involved in the preparation of the “stretch” state $4S_{1/2} |F=4, M=+4\rangle$. (a) Frequency-selective state preparation (FSSP). A 397 nm laser is used to pump population out of the $|F=3, M=+3\rangle$ state, coupled through microwave driving (gray arrows) to all states in the $4S_{1/2}$ manifold except $|F=4, M=+4\rangle$. The hyperfine splitting provides a 2.5 GHz frequency detuning to laser transitions involving $|F=4, M=+4\rangle$, rendering the latter state almost dark to the optical pumping process. (b) Polarization-selective state preparation (PSSP). Here, the 397 nm light targets both hyperfine manifolds of $4S_{1/2}$ through the use of an electro-optical modulator. Using purely σ^+ -polarized light leaves the $|F=4, M=+4\rangle$ state dark to this optical pumping process (indicated by the orange cross). In both schemes, population decaying to the $3D_{3/2}$ manifold is repumped using an 866 nm laser (red).

at room temperature. Our qubit is defined by the hyperfine states $|F=3, M=+1\rangle = |0\rangle$ and $|F=4, M=+1\rangle = |1\rangle$ in the $4S_{1/2}$ ground state manifold. A quantization field of 28.8 mT makes this transition insensitive to magnetic fields (to first order), yielding a so-called “clock” qubit. State preparation of a qubit state is achieved in two steps. The focus of this Letter is the first step, which consists of preparing the $|F=4, M=+4\rangle$ state of the $4S_{1/2}$ ground state manifold, which we refer to as the “stretch” state $|s\rangle$. The second step is to use MW pulses to transfer the population from the stretch state to the $|0\rangle$ qubit state. To readout, MW pulses map the qubit states $|0\rangle$ and $|1\rangle$ to $|s\rangle$ and $|F=3, M=+1\rangle$, respectively, after which optical pulses transfer or “shelve” the $|s\rangle$ state to states in the $3D_{5/2}$ manifold, enabling state-dependent fluorescence [22].

In Table I, we summarize our characterization of the transfer pulse and readout errors, which is necessary to isolate the error in preparing $|s\rangle$ from the total SPAM error. The transfer pulse errors are dominated by (i) leakage to other states occurring during MW oscillator frequency updates, (ii) decoherence during the pulses induced by magnetic field fluctuations, and (iii) accuracy of the pulse amplitude calibration. The readout is limited by (i) off-resonant shelving of the bright state, (ii) spontaneous decay from the shelf states, and (iii) dark counts due to undesired scattering of the 397 nm beam [23]. The characterization of these errors is detailed in Supplemental Material Secs. S2 and S3 [20].

We first discuss the use of a PSSP scheme to prepare the $|s\rangle$ state, illustrated in Fig. 1(b). This relies on purely circularly polarized 397 nm light to excite the $4S_{1/2}$ to $4P_{1/2}$ transition, leaving the $|s\rangle$ state unaffected as it possesses

TABLE I. This error budget shows an estimate of the errors arising from the MW transfer pulses and the optical readout.

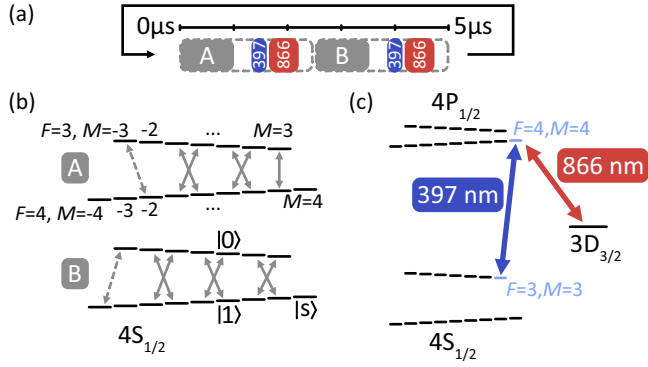
Error ($\times 10^{-5}$)	$ 1\rangle$ (bright)	$ 0\rangle$ (dark)
Leakage	4(4)	5(2)
Decoherence	4.02(14)	7.1(2)
Detuning	0.14(12)	0.3(2)
Amplitude miscalibration	6.2(9)	6.5(9)
Total transfer pulse error	14(4)	19(2)
Off-resonant shelving ^a	25	
Thresholding	3.4(10)	3.4(10)
Shelving failure ^a		4.0
Deshelving ^a		7.6
Total optical readout error	28.4(10)	15.0(10)
Total expected error	42(6)	34(2)
Measured error	49(5)	45(5)

^aSimulation.

no $\Delta M = +1$ transition to $4P_{1/2}$. As a result, the $|s\rangle$ state becomes the steady state of this optical pumping process. An 866 nm laser is used to repump any population that decays to the $3D_{3/2}$ states. To bridge the hyperfine splitting within the $4S_{1/2}$ manifold, we use an electro-optical modulator (EOM), where the EOM-generated sideband drives population out of the $4S_{1/2}$ $F=4$ manifold. As in Ref. [2], the effect of slight impurity in the 397 nm laser polarization is corrected for by driving population out of the $4S_{1/2}$ $F=3$ manifold only (by switching off the EOM) in combination with the MW transfer pulses $|F=4, M=+3\rangle \rightarrow |F=3, M=+3\rangle$ and $|F=4, M=+2\rangle \rightarrow |F=3, M=+2\rangle$. In practice, we find that this last step has a small impact ($\sim 1 \times 10^{-4}$) on the final obtained fidelity, indicating a high purity of our circularly polarized beam. Using PSSP, we measure a SPAM error of $1.4(2) \times 10^{-4}$ for the $|s\rangle$ state (without transfer pulses) which is consistent with the optical readout error for the dark state (see Table I), indicating that the PSSP of $|s\rangle$ introduces only a negligible error. When introducing transfer pulses, we measure a SPAM error (averaged over both qubit states) of $4.7(4) \times 10^{-4}$, which is in reasonable agreement with the error budget in Table I.

As discussed above, restrictions on optical access to the ion or limited control over polarization (for example when using integrated optics) can prohibit the use of PSSP, prompting the FSSP scheme summarized in Fig. 1(a). With this scheme, we extend the MW pulse step implemented at the end of the PSSP [2] to remove the reliance on polarization purity altogether. We first exploit the hyperfine splitting (~ 3 GHz) which greatly exceeds the 397 nm transition linewidth (~ 23 MHz), enabling optical pumping out of the $F=3$ manifold of $4S_{1/2}$ with limited effect on the $F=4$ states. Second, we rely on the large Zeeman shift between hyperfine states (~ 100 MHz) to implement microwave transfer pulses between the $F=3$ and $F=4$ manifold of $4S_{1/2}$ at a ~ 1 MHz Rabi rate without affecting the state to be prepared ($|s\rangle$).

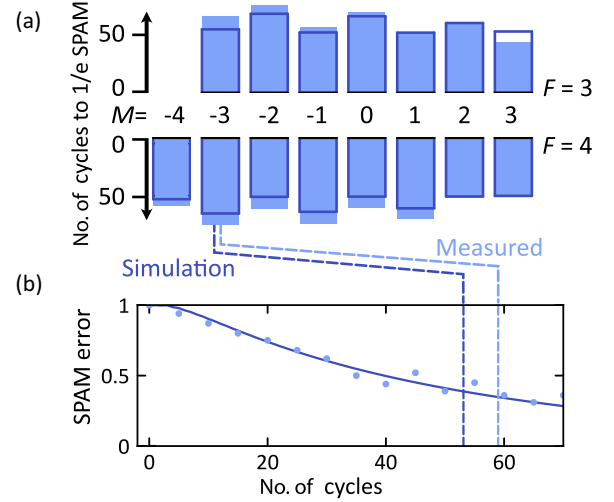
In Fig. 2, the pulse sequence and driving scheme for the FSSP method is illustrated in more detail. The scheme is designed to facilitate comparison to a numerical model, and, to this end, we avoid coupling three or more states together



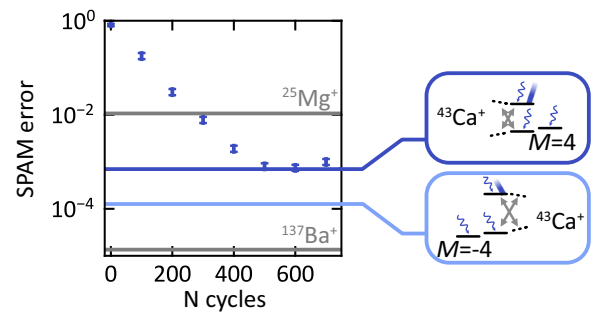
with different driving terms. Avoiding such Λ -type systems allows us to straightforwardly simulate this process using rate equations (see Supplemental Material Sec. S4 [20]). This is achieved by applying the 397 and 866 nm laser pulses sequentially and by using two groups of microwave pulses, also applied sequentially. To simplify the microwave driving, we use the fact that each pair of transitions $M \rightarrow M+1$ and $M+1 \rightarrow M$ are separated by only ~ 160 kHz, and therefore we can drive these transitions simultaneously. Due to the on-chip resonator, centered around our qubit frequency (3.123 GHz), certain transition frequencies [dashed gray in Fig. 2(b)] are strongly suppressed, so we drive these transitions for longer times (during the laser pulses).

We first verify that we can drive population out of every state in the ground state manifold. To do so, a given state is prepared using PSSP and transfer pulses, the FSSP scheme is applied for a varying number of cycles, and then the population in the stretch state is read out through shelving and fluorescence detection. As the data in Fig. 3 show, the scheme is successful regardless of the starting state, and in good agreement with numerical predictions. We then assess the steady-state state-preparation error. As shown in Fig. 4, after 600 cycles (3 ms) of FSSP, state preparation of $|s\rangle$ is achieved with an error of $6.1(11) \times 10^{-4}$. Here, we have subtracted the optical readout error presented in Table I from the total $7.5(11) \times 10^{-4}$ error measured. Again, this error is in good agreement with the numerical prediction of 6.3×10^{-4} state-preparation error.

The FSSP error is limited by off-resonant excitation of $|s\rangle \rightarrow 4P_{1/2}$ transitions. This error scales with $1/\Delta^2$, where Δ is the frequency difference between the 397 nm laser and the frequency of such transitions. Taking into account both the hyperfine splitting and Zeeman shift, we have $\Delta > 2.5$ GHz for all transitions. A first route to lowering the state-preparation error would be to prepare the $|F=4, M=-4\rangle$ state instead,



where the sign of the Zeeman shift works in our favor, increasing the detuning to $\Delta > 3.9$ GHz. We predict an error for the preparation of $|F=4, M=-4\rangle$ of 1.3×10^{-4} . However, in our experimental setup, the on-chip resonator suppresses the amplitude of the transfer pulses necessary to transfer $|F=4, M=-4\rangle$ to a qubit state. As a consequence, these



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transfer pulses would be significantly slower than those we typically use, resulting in a SPAM error limited by decoherence affecting these pulses.

A larger hyperfine splitting is therefore advantageous, making this technique particularly well suited to heavier ions. We extend our simulation to other isotopes at “intermediate-field,” i.e., at static fields where the first clock transition which is not $M = 0 \leftrightarrow M = 0$ appears in the ground state. As expected, we find that the error worsens for a lighter ion (we predict 1.1×10^{-2} for preparing the $|F = 3, M = -3\rangle$ state in $^{25}\text{Mg}^+$) and improves for a heavier ion (1.4×10^{-5} error for preparing the $|F = 2, M = 2\rangle$ state in $^{137}\text{Ba}^+$). These predictions are shown in Fig. 4 alongside our experimental results.

Finally, another route to lowering the error is to purify the polarization of the 397 nm light, as, through selection rules, this limits the probability of off-resonantly driving population out of the $|s\rangle$ state. In the experiments and simulations above, we used linearly polarized 397 nm light, orthogonal to the quantization axis, which drives σ^+ and σ^- transitions. The 397 nm intensity was $0.05I_0$, where I_0 is the saturation intensity of the 397 nm transition. Since the laser is centered on a σ^+ transition, if the σ^- and/or π polarization component is minimized, the desired optical pumping process out of the $F = 3$ state is reduced, while increasing the probability of σ^- and/or π photons exciting a $|s\rangle \rightarrow 4P_{1/2}$ transition. To illustrate this, we rotate the beam’s linear polarization axis to have a 45° angle with respect to the quantization axis (rather than 90° as above). This allows the 397 nm laser to off-resonantly drive π transitions in addition to σ^+ and σ^- transitions. In this case we measure an error of $1.9(3) \times 10^{-3}$ in preparing $|s\rangle$, which is close to our simulated error of 1.5×10^{-3} and about three times worse than with σ^+/σ^- polarization. Hence, although the FSSP scheme is still somewhat sensitive to polarization, it is orders of magnitude less sensitive than the PSSP scheme (see Supplemental Material Sec. S6 [20]).

In the implementation of FSSP described in Figs. 2–4, the scheme is significantly slower (3 ms) than the PSSP (600 μs), and is limited in speed by the MW operations. Since the smallest detuning between a driven MW transition, and a MW transition involving the stretch state, is 240 MHz, the total MW pulsing duration could be lowered by approximately one order of magnitude, from 5 μs to ≈ 500 ns per cycle (allowing for a 1×10^{-4} off-resonant excitation error), giving a state-preparation time of 300 μs . Further speed-up could then be obtained through pulse shaping, or by steadily increasing the pulse time as the state-preparation progresses. In practice, the on-chip resonator prohibits the driving of all MW transitions at sufficient amplitude, and we restrict the maximum injected MW power to 1 W per frequency tone, which ultimately limits the speed of our state-preparation scheme.

Since most of the microwave transitions are only driven for a fifth of the total cycle time, we also implement a “continuous” version of FSSP, where all laser and microwave fields are kept on in an attempt to speed up the state-preparation time. However, in doing this, we can no longer benefit from comparing experimental data to the rate equation model. As already identified in simulations of the pulsed implementation (see Supplemental Material Sec. S4 [20]), the intensity of the 397 nm light has a large influence on the process: A

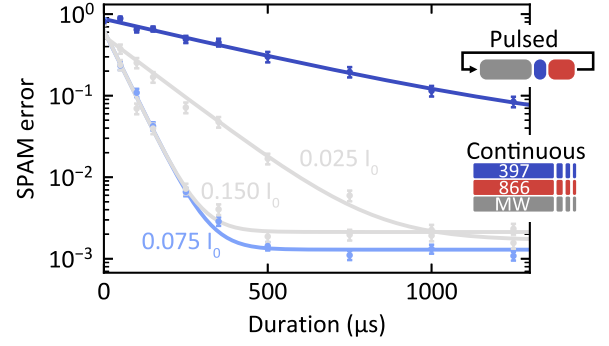


FIG. 5. Continuous-wave implementation of FSSP. State-preparation and measurement (SPAM) error measured in a continuous implementation of FSSP (light blue, gray) and compared to the pulsed implementation (dark blue, described in Fig. 2). The multiple data sets for the continuous case reveal the influence of 397 nm laser intensity on the state-preparation error and duration. At low intensity (gray, $0.025I_0$), convergence of the error is slower, with little advantage in error. When higher intensities are used (gray, $0.150I_0$), convergence occurs on a similar timescale, but the error is larger due to off-resonant excitation of the target state. We therefore empirically find an optimal intensity of $0.075I_0$ (light blue).

high intensity increases the error, and a low intensity slows down the state preparation with marginal reduction in the error. In the absence of a reliable numerical model, we sweep the laser intensity to experimentally determine the optimal setting. The SPAM error for varying 397 nm light intensity is depicted in Fig. 5, highlighting the good balance between speed and error obtained with $I = 0.075I_0$. The continuous implementation reduces the time required to prepare $|s\rangle$ from 3 ms to 750 μs , at the expense of a small increase in the $|s\rangle$ state-preparation error. When combined with the microwave transfer pulses to the qubit state, the qubit state-preparation and measurement error is measured to be $1.2(1) \times 10^{-3}$, with a duration of 838 μs . After subtraction of the measured read-out and transfer pulse errors [$4.7(4) \times 10^{-4}$], we attribute an error of $7.5(13) \times 10^{-4}$ to the state preparation of $|s\rangle$ through continuous FSSP.

In conclusion, we have introduced a frequency-selective state-preparation (FSSP) method that does not rely on pure laser polarization and is applicable to various ion species with nuclear spin $I > 1/2$ operated at “intermediate field.” In Table II, we summarize the achieved state-preparation errors. We report a SPAM error of $1.2(1) \times 10^{-3}$ in 840 μs using this method. We compare this to our implementation of a polarization-selective state-preparation method, with which we obtain a SPAM error of $4.7(4) \times 10^{-4}$ in 1.2 ms. The latter is an improvement on the previous state of the art [2] for intermediate-field $^{43}\text{Ca}^+$ [$6.8(5) \times 10^{-4}$ SPAM error with a state-preparation duration of 930 μs]. In our implementation of the FSSP, both error and state-preparation durations are limited by the design of our surface trap chip which features an on-chip resonator. Without resonant suppression of certain transitions, we would be able to raise the microwave driving rate, enabling us to lower the pulse duration by at least an order of magnitude without impacting the error, corresponding

TABLE II. This table summarizes the state-preparation errors presented in this Letter (excluding transfer pulses, see Table I). In the method column, “C” and “P” correspond to continuous and pulsed schemes, respectively. The durations correspond to the experimental implementations. Theoretical durations can be as short as 75 μ s if sufficient microwave power is available.

Pol. σ^+, σ^-, π	Method	State $ F, M\rangle$	Theory ($\times 10^{-4}$)	Experiment ($\times 10^{-4}$)	Duration (ms)
σ^+	C and P	$ 4, +4\rangle$		$\lesssim 0.1$	0.6
σ^+/σ^-	P	$ 4, +4\rangle$	6.3	6.1(11)	3
σ^+/σ^-	C	$ 4, +4\rangle$		7.5(13)	0.75
σ^+/σ^-	P	$ 4, -4\rangle$	1.3		
$\sigma^+/\sigma^-/\pi$	P	$ 4, +4\rangle$	15	19(3)	15

to <300 and $<75 \mu$ s for the pulsed and continuous implementations, respectively. We would also be able to transfer the $|F = 4, M = -4\rangle$ state to the qubit without being overly affected by decoherence in the transfer pulses, and so, by preparing this state with FSSP rather than $|F = 4, M = 4\rangle$, could theoretically lower the error to $\sim 1 \times 10^{-4}$. Moreover,

fidelity could be enhanced by transitioning to heavier ions, thereby increasing the hyperfine splitting and reducing the fundamental error source: off-resonant driving bridging the hyperfine splitting. Even without these improvements, the measured SPAM errors lie significantly below quantum error correction thresholds of $\approx 1\%$ [24], and therefore can be readily used in a quantum computing setting.

This scheme will simplify the scaling of ion-trap-based quantum computers using integrated optics, where purely circularly polarized light is difficult to engineer. It also allows for simpler laser delivery systems to control ions, with fewer beam paths and free-space optical components, and lesser requirements on the quantization field direction. Furthermore, this scheme could be applied to the state preparation of optical and metastable state qubits [25].

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