

A versatile multi-tone laser system for manipulating atomic qubits based on a fiber Mach–Zehnder modulator and second harmonic generation

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Abstract: Stimulated Raman transition is a fundamental method to coherently manipulate quantum states in different physical systems. Phase-coherent dichromatic radiation fields matching the energy level splitting are the key to realizing stimulated Raman transition. Here we demonstrate a flexible-tuning, spectrum-clean and fiber-compatible method to generate a highly phase-coherent and high-power multi-tone laser. This method features the utilization of a broadband fiber Mach–Zehnder modulator working at carrier suppression condition and second harmonic generation. We generate a multi-tone continuous-wave 532 nm laser with a power of 1.5 Watts and utilize it to manipulate the spin and motional states of a trapped $^{171}\text{Yb}^+$ ion via stimulated Raman transition. For spin state manipulation, we acquire an effective Rabi frequency of $2\pi \times 662.3$ kHz. Due to the broad bandwidth of the fiber modulator and nonlinear crystal, the frequency gap between tones can be flexibly tuned. Benefiting from the features above, this method can manipulate $^{171}\text{Yb}^+$ and $^{137}\text{Ba}^+$ simultaneously in the multi-species ion trap and has potential to be widely applied in atomic, molecular and optical physics.

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1. Introduction

As a fundamental method in atomic, molecular and optical researches [1,2], stimulated Raman transition (SRT) is widely used to manipulate spin states in different physical systems, such as ultra-cold atoms [3,4], ultra-cold molecules [5,6], trapped ions [7–9] and superconducting circuits [10]. Mode-locked lasers, master-slave lasers and directly modulated continuous-wave lasers are common tools to generate frequency splitting in optical fields. These existing tools have their unique advantages, while some inconveniences still occur in the experiments.

Mode-locked lasers have natural broad bandwidth, which are typically used to implement SRT for trapped ions such as $^9\text{Be}^+$ ion [11] or $^{171}\text{Yb}^+$ ion [12–16]. The mode-locked lasers generate a train of frequency combs with a spectrum range around hundreds of GHz while the repetition rate is fixed. Therefore, additional optical modulators are required to realize precise frequency matching between comb teeth and the qubit energy levels. However, it is necessary to avoid unwanted resonant or off-resonant drive of multiple energy levels from the redundant frequency combs. Besides, the pulsed lasers are incompatible with optical fibers because of pulse broadening caused by the chirp effect, which decreases the flexibility of the optical configurations.

For continuous-wave (CW) laser, master-slave laser systems with optical phase-lock loops (OPLL) technique [17–19] or sideband injection-locking technique [20,21] are commonly used to generate two phase-coherent Raman lasers with adequate power. For the OPLL technique, the phase noise is limited by the performance of electrical servo loops. For the sideband injection-locking technique, the slave laser is locked to a specific sideband generated by optical modulators and filtered by resonant Fabry-Pérot cavities [20]. The master-slave laser has a clean spectrum that only contains those desired frequency components used to implement SRT, but the beat note between the master laser and slave laser can't be tuned optionally. Master-slave laser systems are widely used in the experiments of ultra-cold atoms like ^{87}Rb [21] or trapped ions like $^9\text{Be}^+$ [22]. For $^9\text{Be}^+$, additional second harmonic generation (SHG) or sum frequency generation (SFG) is required to convert the infrared laser to a wavelength near the D_1 line of ion [22,23]. Master-slave laser systems demand two or more independent lasers [21] and complicated electronic systems, which increases system complexity and cost.

Another option is to use a phase electro-optic modulator to directly generate two sidebands in a single CW laser. The narrow frequency shift ranges of resonant electro-optical modulators (EOMs) limit the performance of the Raman laser system [24]. To extend the tuning range, fiber EOMs with broad frequency shift ranges are required [25]. The fiber EOMs usually work in an infrared domain while the D_1 lines of the trapped ions are typically in the ultraviolet or blue domain. The extremely large detuning between the infrared laser and D_1 lines of trapped ions will result in a quite low effective Rabi frequency. To avoid that, an SHG process is needed to realize wavelength conversion from infrared to a shorter wavelength. However, the spectrum of phase-modulated laser will contain redundant components, which decreases the efficiency of the SHG process and leads to a low effective Rabi frequency.

To acquire a clean spectrum that only contains those desired components, intensity modulation which can effectively suppress unwanted components is applied in our method. In this paper, we use a fiber Mach-Zehnder modulator (FMZM) to generate the multi-tone laser that is used to manipulate hyperfine ground states. We use a Yb-doped fiber amplifier to acquire a steady high power laser and a periodically polarized lithium niobate (PPLN) crystal to achieve wavelength conversion by the SHG process. We investigate the performance of this method by implementing spin or motional state manipulation of $^{171}\text{Yb}^+$ ion confined in a high optical access Paul trap. Compared to the phase modulation, We achieve carrier suppression to eliminate redundant frequency components. Compared to the mode-locked pulse laser, this continuous laser in the visible domain is easily coupled into fiber to improve the scalability of the system. Compared to the master-slave laser, a single directly-modulated laser effectively reduces the complexity and cost of the system. Benefiting from the board bandwidth of FMZM and PPLN crystal, the frequency gap between tones can be tuned optionally from a few MHz to dozens of GHz.

2. System setup and characterization

The setup for laser beams generation is depicted in Fig. 1(a). A frequency-locked monochromatic laser of 1064 nm that only contains one frequency component is sent into an FMZM with a 20 GHz bandwidth (iXblue, NIR-MX-LN-20). The two portions of the output optical signal of FMZM are sent into a Yb-doped fiber amplifier (YDFA) and an electrical servo system respectively. The amplified laser propagates through a PPLN crystal to convert the wavelength of the laser from infrared to visible via an SHG process. The spectrum diagram of the input signal of FMZM is shown as Fig. 1(b). The half-wave plate here is used to rotate the polarization of the laser to align the principal axis of FMZM, which helps to reach the maximum transmission efficiency. The FMZM has a built-in Mach-Zehnder interferometer (MZI) to implement intensity modulation on the optical signal. A bias control port is used to change the operating point of FMZM while a radio frequency (RF) control port is used to modulate the optical signal with

high frequency. By applying different voltages to the bias control port, the FMZM operates at different operating points.

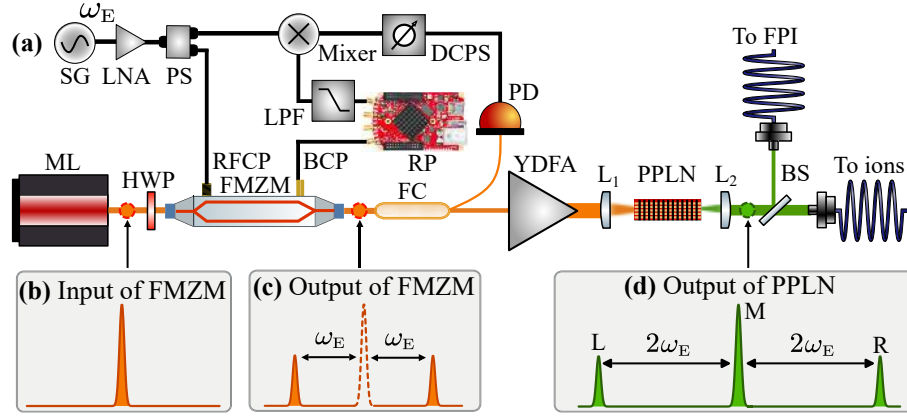


Fig. 1. (a) Schematic of the setup of laser beams generation. A master oscillator power amplifier system provides the high-power multi-tone laser. A signal generation and servo system are used to maintain the operating point of FMZM. (b) The diagram spectrum of the input signal of FMZM. (c) The diagram spectrum of the output signal of FMZM. (d) The diagram spectrum of the output signal after the SHG process. ML: monochromatic laser, HWP: half-wave plate, RFCP: radio-frequency control port, BCP: bias control port, FMZM: fiber Mach-Zehnder modulator, FC: fiber coupler, YDFA: Yb-doped fiber amplifier, PCL: planoconcave lens, PPLN: periodically polarized lithium niobate, BS: beam splitter, LPF: low pass filter, RP: red pitaya, PD: photoelectric detector, SG: signal generator, LNA: low-noise amplifier, PS: power splitter, DCPS: digital control phase shifter.

If the input optical field of the PPLN crystal contains redundant frequency components, the corresponding output optical field will contain more frequency components, which decreases the efficiency of YDFA and causes a harmful influence on our coherent manipulation. To generate the desired frequency splitting in the 1064 nm laser and acquire a clean spectrum simultaneously, we have to eliminate the carrier component and reserve two sideband components. When the FMZM operates at its maximum extinction point, the carrier vanishes due to the destructive interference effect of MZI. When the voltage applied to the RF control port is appropriate, only two lowest-order sidebands remain. It is called carrier suppression and double sideband (CS-DSB) modulation [26].

The RF signal, of which the frequency equals half of the energy level splitting of a certain physical system, is generated by a signal generator (Rohde & Schwarz, SMB100A). In this paper, it is 6.32 GHz for $^{171}\text{Yb}^+$ hyperfine qubit. This signal is amplified by a low-noise amplifier (Mini-Circuits, ZX60+). Then it is divided into a driving signal and a demodulation signal with a 2-channel power splitter. To realize CS-DSB modulation, the FMZM firstly has to operate at the maximum extinction point, in which case the carrier component is eliminated by the destructive interference effect of the M-Z interferometer. Then the driving signal has to be adjusted to an appropriate power to avoid the appearance of those high-order sidebands, known as the weak modulation condition. The output signal of FMZM only contains two sidebands and the frequency gap equals the energy level splitting in the case of CS-DSB modulation. The diagram of the output optical signal of FMZM is shown as Fig. 1(c). Typically, the electric field of the output signal of FMZM is

$$E_{\text{out}}(t) = \alpha E_{\text{in}}(t) \cos \left[\frac{\Delta\varphi_b}{2} + \frac{\Delta\varphi_R}{2} \sin(\omega_E t) \right] e^{j\frac{\Delta\varphi_b}{2}} \quad (1)$$

where α is the insertion loss of FMZM, $E_{\text{in}}(t)$ is the electric field of incident laser of FMZM and $E_{\text{in}}(t) = E_{\text{in}} e^{j\omega t}$, $\Delta\varphi_{\text{b}}$ is the phase shift caused by the bias voltage applied to the bias control port, $\Delta\varphi_{\text{R}}$ is the phase shift caused by the driving signal applied to the RF control port, ω_{E} is the frequency of the driving signal. In the condition of maximum extinction point ($\Delta\varphi_{\text{b}} = \pi$), the electric field of the output signal of FMZM is derived from Eq. (1) as

$$E_{\text{out}}(t) = -2\alpha j E_{\text{in}}(t) \left\{ \sum_{n=1}^{\infty} J_{2n-1} \left(\frac{\Delta\varphi_{\text{R}}}{2} \right) \sin[(2n-1)\omega_{\text{E}}t] \right\} \quad (2)$$

in where $J_n(\Delta\varphi_{\text{R}})$ is the n -order Bessel function. Experimentally, we carefully adjust the amplitude of the driving signal to satisfy the weak modulation condition, resulting in that $\Delta\varphi_{\text{R}} = 0.12$. In the condition of weak modulation, the high-order Bessel function could be truncated and the electric field of the output laser of FMZM is

$$E_{\text{CS-DSB}}(t) \approx \frac{\alpha \Delta\varphi_{\text{R}}}{4} E_{\text{in}} \left(e^{j(\omega - \omega_{\text{E}})t} - e^{j(\omega + \omega_{\text{E}})t} \right) \quad (3)$$

where $E_{\text{CS-DSB}}(t)$ is the electric field of the output laser of FMZM when it operates at CS-DSB situation. As Eq. (3) shows, in the case of CS-DSB modulation, the carrier component is sufficiently suppressed while only two first-order sideband components are reserved. The intensity of output laser is

$$I_{\text{CS-DSB}} = \frac{\alpha^2 E_{\text{in}}^2}{2} \frac{(\Delta\varphi_{\text{R}})^2}{4} [1 - \cos(2\omega_{\text{E}}t)] \quad (4)$$

Suffering from a variety of perturbations, e.g. temperature, working time and static electricity, the operating point of FMZM will drift. To steadily achieve CS-DSB modulation, we have to lock the operation point of FMZM at its maximum extinction point by feeding back a control signal through the bias control port [27,28]. The output of FMZM is sent into a 2×2 polarization-maintaining fiber beam splitter of which the output power ratio is 9 to 1. The low-power portion is fed into a high-speed photoelectric detector, which transforms the optical signal into an electrical signal. A demodulation signal which has the same frequency as the driving signal of FMZM is mixing with the electrical signal of the photoelectric detector, as Eq. (1) is shown. After the low-pass filtering process, an error signal that contains the information about bias voltage drift is acquired. The error signal is fed into a Red Pitaya STEMLab 125-14 board that implements a digital Proportion-Integration-Differentiation (PID) control. By locking the error signal at its zero point where $\Delta\varphi_{\text{b}} = \pi$, the FMZM operates at maximum extinction point steadily.

The high-power portion of the fiber beam splitter is amplified by the YDFA (Precilasers, YDFA-SF-1064-8W-CW). The output laser power of the YDFA is 8 W. Then the amplified laser is focused by a planoconcave lens to propagate through a periodically polarized lithium niobate (PPLN) crystal with a beam waist of 59 μm . This SHG process converts the 1064 nm incident laser with two sidebands into the 532 nm multi-tone laser with three frequency components and a power of 1.5 W. For the 532 nm multi-tone laser, the frequency gap between adjacent tones equals the double frequency of the driving signal of FMZM. The diagram of the spectrum of 532 nm multi-tone laser is shown as Fig. 1(d). For the sake of clarity, the sidebands in Fig. 1(d) from left to right are marked as L, M and R.

To characterize the bandwidth of the PPLN crystal, we tune the frequency of the 1064 nm laser with dozens of GHz and measure the output power of the 532 nm laser. The result is shown as Fig. 2(a). When the temperature of the PPLN crystal is constant, the efficiency of the SHG process has a strong correlation with the frequency of the 1064 nm incident laser. There are two frequencies corresponding to the maximum SHG efficiency of which the interval is about 20 GHz and the center wavelength of this PPLN crystal is 1064.5720 nm. Broad bandwidth of

PPLN crystal means that high SHG efficiency can be obtained even if the frequency splitting of multi-tone laser is high. It indicates that we can flexibly tune the frequency gap between laser tones to match the energy level splittings of the different physical systems.

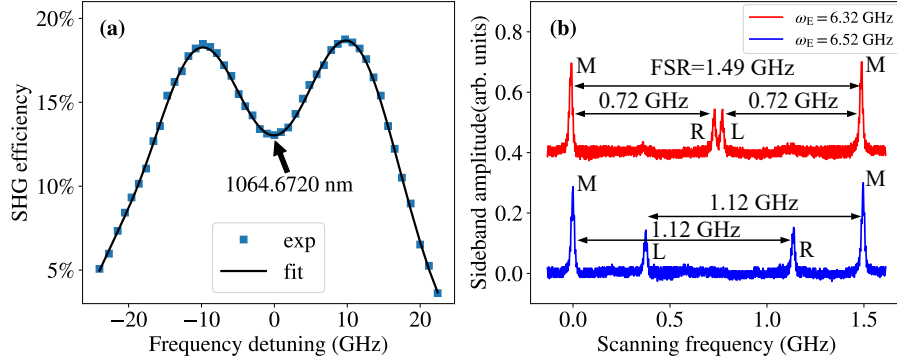


Fig. 2. (a) The SHG efficiency measurement with frequency detuning of incident laser when the crystal temperature is 91.86°C. The center wavelength of the PPLN crystal is 1064.5720 nm while the two frequency corresponding to maximum efficiency has a 10 GHz detuning from it. (b) Sideband spectra of 532 nm laser measured with an FPI. The free spectral range (FSR) of the FPI is 1.49 GHz. The high peaks correspond to the sideband M in Fig. 1(d) while the peaks located in the middle of high peaks correspond to sideband L and R. When the driving frequency of FMZM is set to 6.32 GHz (6.52 GHz), the frequency gap between sideband L or R with sideband M is 12.64 GHz (13.04 GHz). The peak which has a distance of $8 \times \text{FSR} + 0.72\text{GHz}$ (1.12 GHz) from the high peak is marked as sideband L or R.

To characterize the sidebands of the 532 nm multi-tone laser, its spectrum is measured by a scanning Fabry-Pérot interferometer (FPI, Thorlabs, SA200-3B). The measured sideband spectrum recorded by an oscilloscope is shown as Fig. 2(b). The sidebands appear at the corresponding position with their respective frequency when the driving frequency of FMZM is set as 6.32 GHz and 6.52 GHz respectively. The 532 nm multi-tone laser used to drive the stimulated Raman transition is coupled to the polarization-maintaining optical fiber for experimental usage. The fiber-compatible feature is good to improve the scalability of the system.

3. Experiment verification

In this paper, we utilize this method to manipulate $^{171}\text{Yb}^+$ ion [29]. As Fig. 3 shows, the energy levels that involve quantum logical operation for $^{171}\text{Yb}^+$ are $|0\rangle \equiv {}^2S_{1/2}|F=0, m_F=0\rangle$ and $|1\rangle \equiv {}^2S_{1/2}|F=1, m_F=0\rangle$ with a 12.64 GHz of hyperfine ground state splitting (HFS), denoted as ω_{HF} . We experimentally investigate the performance of this 532 nm multi-tone laser. As a first demonstration, we utilize it to drive the spin states of a single $^{171}\text{Yb}^+$ ion confined in a glass cell Paul trap with high optical access in multi-directions [30]. The experimental setup for driving stimulated Raman transitions is shown in Fig. 3.

As Fig. 4 shows, the laser is divided into two portions with a beam splitter. They both propagate through an acousto-optic modulator (AOM, Gooch & Housego, 3200-121) for frequency shifting, an acousto-optic deflector (AOD) for positioning the beam for single ion addressing and a lens for light spot focusing. For convenience of description, we denote the portion of laser that propagates through AOM₁, AOD₁, M₁ and L₁ as Raman beam I. The other portion is denoted as Raman beam II. Both Raman beam I and II propagate in a perpendicular direction to the glass cell while the cooling, ionization, and repumping lasers come from other direction in the horizontal plane. The orientations of the laser beams form an effective wave vector difference $\vec{\Delta k} = \vec{k}_1 - \vec{k}_2$ along the magnetic field $\vec{B}$ lines, which is also one of the radial directions. The driving frequency of

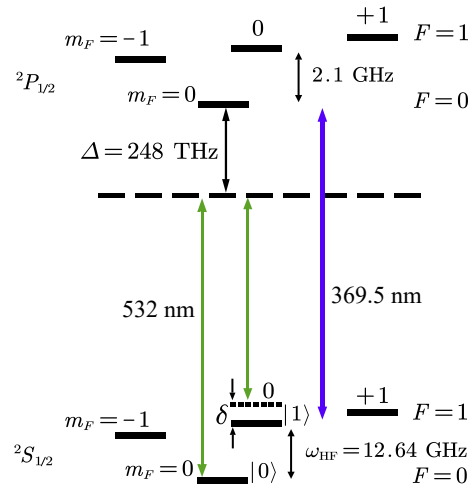


Fig. 3. Energy level scheme for $^{171}\text{Yb}^+$. The purple solid line represents the energy levels that involve Doppler cooling and the transition wavelength is 369.5 nm. In the experiment, a 14.7 GHz sideband of the 369.5 nm laser is required to bring the ions back to the cooling cycle if the ions fall into dark state. The 532 nm multi-tone laser is detuned by $\Delta \approx 248$ THz from the transition between $^2S_{1/2}|F=1, m_F=0\rangle$ and $^2P_{1/2}|F=1, m_F=0\rangle$.

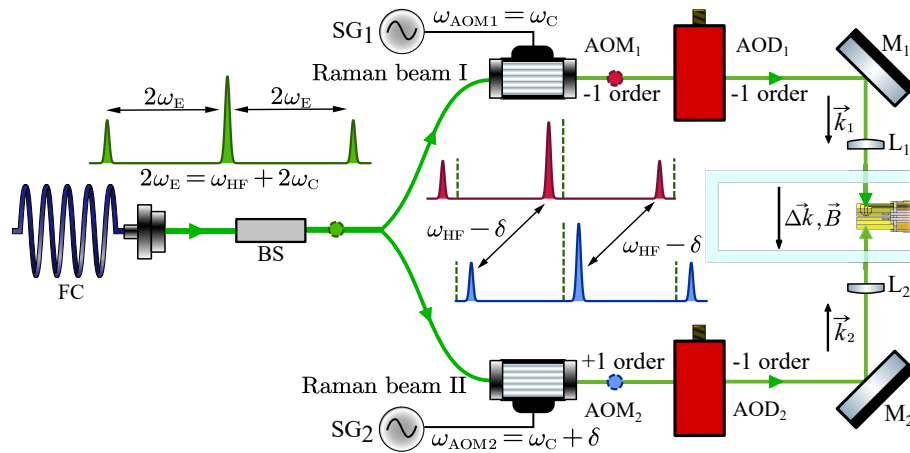


Fig. 4. Simplified schematic of the experimental setup for driving stimulated Raman transitions. The 532 nm laser is emitted from a fiber optic coupler. A beam splitter is used to divide the laser into two parts which propagate through two optical paths. The lenses are used to focus the spots of laser beams to acquire a higher Rabi frequency. Some optical components used for rotating polarization of laser beams aren't shown in this schematic. FC: fiber coupler, BS: beam splitter, SG_i: signal generator, AOM_i: acousto-optic modulator, AOD_i: acousto-optic deflector, M_i: mirror, L_i: lens.

FMZM, namely ω_E , is set as 6.32 GHz so that Raman beam I and Raman beam II can drive the spin state independently, which helps to overlap both the Raman beams with the ion. The driving frequencies of AOM₁ and AOM₂, namely ω_{AOM1} and ω_{AOM2} , are set as ω_C and $\omega_C + \delta$ respectively, while -1 st diffraction order of AOM₁ and $+1$ st diffraction order of AOM₂ are used. Here the δ is the single-photon detuning and it is set as 0 MHz to resonantly excite the spin state. The center frequency of AOMs is $\omega_C = 200$ MHz for type 3200-121 from Gooch & Housego. The driving frequency of AOD₁ and AOD₂ is set as their center frequency and both the -1 st diffraction order of AODs are used.

The ion is prepared in the $|0\rangle$ by Doppler cooling and optical pumping. The Doppler cooling laser is 10 MHz red-detuned from the cooling transition in order to optimize the efficiency of Doppler cooling. Meanwhile, a 14.7 GHz sideband for the cooling laser is needed to couple the $|0\rangle$ and $^2P_{1/2}|F = 1, m_F = 0\rangle$, so the ion will return to the cooling cycle when it falls into the dark state accidentally. To overlap the Raman beam I with ion position, we scan the position of the laser spot with a fixed interaction time. The increase of fluorescence counting detected by the photo-multiplier tubes (PMT) indicates that the light spot starts overlapping with the ion. The next step is optimizing the laser position and spot size according to the variation of fluorescence counting until a maximum fluorescence counting is reached. Then we reduce the interaction time and repeat the aforementioned steps to acquire the maximum Rabi frequency. The ion flips its spin state at a frequency of $2\pi \times 662.3$ kHz when the power of Raman beam I is approximately 750 mW and the beam waist is approximately 2.5 μm . The excitation probability of ion versus interaction pulse time is plotted as Fig. 5(a).

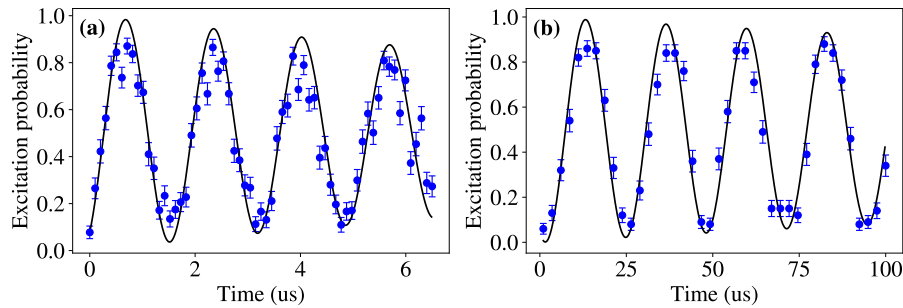


Fig. 5. (a) The Rabi flopping driven by Raman beam I independently with a Rabi frequency of $2\pi \times 662.3$ kHz. Only Doppler cooling is implemented on the ion. (b) The carrier Rabi flopping driven by Raman beam I and II as counter-propagating laser with a Rabi frequency of $2\pi \times 42.5$ kHz. Doppler cooling and EIT cooling are implemented on the ion.

In the Rabi flopping experiment, the ion is illuminated by a sequence of Doppler cooling laser and pumping laser with 1 ms and 30 μs duration, then the ion is driven by the Raman operation laser for a varying interaction time. We detect the spin state 100 times with a 1 ms detecting laser for each experiment to acquire the excitation probability, which means the probability of the ion is in the $|1\rangle$ state. For Raman beam II we implement the same procedures to acquire the maximum Rabi frequency. After both Raman beam I and II are overlapped with ion, they illuminate the ion simultaneously and the length of optical paths of Raman beam I and II is adjusted to be equal to each other to acquire a maximum Rabi frequency in the condition of two independent Raman beams excitation.

The next demonstration is driving motional states of ions with Raman beam I and II as counter-propagating Raman beams. Firstly, we reduce the power of laser and switch the driving frequency of FMZM as $\omega_E = \omega_{HF}/2 + \omega_C$, which is 6.52 GHz. In the position of the green dot shown in Fig. 4, the frequency gap between adjacent components is $2\omega_E = 13.04$ GHz. The driving frequencies of AOMs are set as $\omega_{AOM1} = \omega_C$ and $\omega_{AOM2} = \omega_C + \delta$ respectively, where δ

is the frequency of motional state. All spectrum components of Raman beam I have a red-shift of ω_C while those of Raman beam II have a blue-shift of $\omega_C + \delta$, which are corresponding to the red dot and blue dot shown in Fig. 4 respectively. The frequency gap between the center component of Raman beam I and the left component of Raman beam II is $\omega_{HF} - \delta$. The same situation goes for the right components of Raman beam I and the center components of Raman beam II. When $\delta = 0$ MHz, the ion performs carrier rabi flopping without changing its motional state. The excitation probability of ion versus interaction pulse time is plotted as Fig. 5(b). Compared to the situation in Fig. 5(a), electromagnetically induced transparency (EIT) cooling [31,32] with a 1 ms duration is added into the experiment sequence, after the Doppler cooling while before the pumping. We trap two ions and investigate the frequencies of all the motional states of ions. The ions are illuminated by counter-propagating Raman beams for a fixed interaction time while the value of δ is changing. A certain motional state would be driven if δ equals its frequency. In the condition of $\delta > 0$ MHz, the frequency gap between aforementioned components will be less than ω_{HF} and red sidebands will be driven. Otherwise the blue sidebands will be driven. In our experiment, we vary the value of δ from 0.7 MHz to 1.6 MHz with a step of 2 kHz, which is enough to cover the frequencies of all motional modes of radial direction. Analogously, we repeat the same experiment sequence 100 times for each value of δ , in which the ion is illuminated by the Doppler cooling laser, EIT cooling laser, pumping laser, Raman operation laser and detecting laser in sequence for 1000 μ s, 1200 μ s, 30 μ s, fixed interaction time and 1000 μ s respectively. The four radial motional states of two ions in the same potential are driven and then their frequencies are obtained by fitting the profile of data, as 1.164 MHz, 1.262 MHz, 1.417 MHz and 1.499 MHz respectively (see Fig. 6(a)). Then we set $\delta = 1.499$ MHz, which is the frequency of center-of-mass mode in the x -direction. With the same experiment sequences, we can observe a blue sideband Rabi flopping with a Rabi frequency of $2\pi \times 6.28$ kHz as Fig. 6(b). By thermal state fitting, the average phonon number is obtained as $\bar{n} = 0.33$, which is close to the quantum ground state.

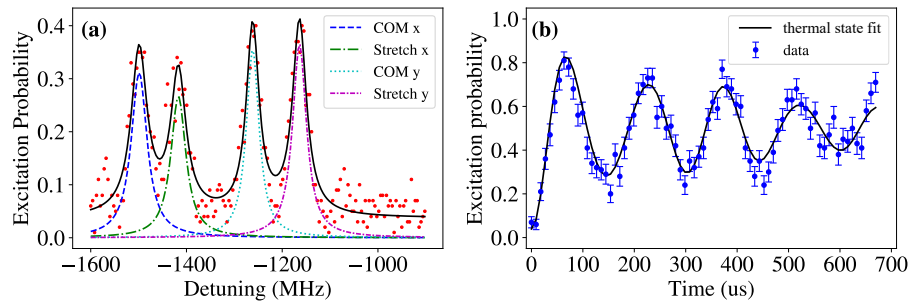


Fig. 6. (a) The phonon spectrum of two ions. The colored lines are Lorentz profile fit to the data. The horizontal axis is the frequency detuning from the central resonance frequency. The highest excitation probability indicates that the corresponding frequency detuning equals the frequency of a certain motional state. (b) Blue sideband Rabi flopping of the ion after sideband cooling and EIT cooling with a Rabi frequency of $2\pi \times 6.28$ kHz. The average phonon number $\bar{n} = 0.33$ according to the thermal state fitting result.

4. Conclusion and outlook

We demonstrate a solid-state laser system that generates a multi-tone laser based on an intensity-modulated fiber amplifier and SHG process, and we apply it to manipulate the spin states and motional states for $^{171}\text{Yb}^+$ ion. An FMZM is used to generate two consistent sidebands which bridge the hyperfine ground states of the ion. In the weak modulation situation, we lock the

FMZM at its maximal extinction point to acquire a clean spectrum of Raman laser, in which the redundant frequency components are suppressed. Visible light converted from the SHG process can be coupled into fiber to improve the scalability of the system. Benefiting from the wide tuning range of FMZM and broad bandwidth of PPLN crystal, this system has the potential to be employed for other species of atomic qubits. Considering that $^{171}\text{Yb}^+$ with D_1 line of 369 nm and HFS of 12.64 GHz [33], $^{137}\text{Ba}^+$ with D_1 line of 493 nm and HFS of 8.04 GHz [34]. By switching the driving frequency of FMZM, we can utilize this method to perform SRTs on $^{171}\text{Yb}^+$ and $^{137}\text{Ba}^+$ simultaneously, which indicates that this method has the potential to be applied to hybrid systems. In addition, ^{87}Rb is commonly used as a platform for cold atom experiments with D_1 line of 780 nm and HFS of 6.834 GHz. One can use an Erbium-doped laser amplifier instead of YDFA to amplify a monochromatic laser of 1560 nm and convert the multi-tone laser to 780 nm with the SHG process, which indicates its potential for cold atoms experiments. This flexible-tuning, spectral-clean and fiber-compatible method combines the advantages of existing tools used to implement stimulated Raman transition (SRT). Thanks to the features above, this method can manipulate multiple species of atomic spins, leading to a potential to be widely used in atom, molecule and optics (AMO) fields.

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Data availability. The data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References

1. K. Bergmann, H. Theuer, and B. W. Shore, "Coherent population transfer among quantum states of atoms and molecules," *Rev. Mod. Phys.* **70**(3), 1003–1025 (1998).
2. N. V. Vitanov, A. A. Rangelov, B. W. Shore, and K. Bergmann, "Stimulated Raman adiabatic passage in physics, chemistry, and beyond," *Rev. Mod. Phys.* **89**(1), 015006 (2017).
3. J. Bateman, A. Xuereb, and T. Freegarde, "Stimulated Raman transitions via multiple atomic levels," *Phys. Rev. A* **81**(4), 043808 (2010).
4. M. Kasevich and S. Chu, "Atomic interferometry using stimulated Raman transitions," *Phys. Rev. Lett.* **67**(2), 181–184 (1991).
5. U. Gaubatz, P. Rudecki, S. Schieman, and K. Bergmann, "Population transfer between molecular vibrational levels by stimulated Raman scattering with partially overlapping laser fields. A new concept and experimental results," *J. Chem. Phys.* **92**(9), 5363–5376 (1990).
6. P. Král and M. Shapiro, "Cyclic population transfer in quantum systems with broken symmetry," *Phys. Rev. Lett.* **87**(18), 183002 (2001).
7. J. L. Sørensen, D. Møller, T. Iversen, J. B. Thomsen, F. Jensen, P. Staunum, D. Voigt, and M. Drewsen, "Efficient coherent internal state transfer in trapped ions using stimulated Raman adiabatic passage," *New J. Phys.* **8**(11), 261 (2006).
8. C. M. Seck, M. G. Kokish, M. R. Dietrich, and B. C. Odom, "Raman sideband cooling of a $^{138}\text{Ba}^+$ ion using a Zeeman interval," *Phys. Rev. A* **93**(5), 053415 (2016).
9. M. L. Cai, Z. D. Liu, W. D. Zhao, Y. K. Wu, Q. X. Mei, Y. Jiang, L. He, X. Zhang, Z. C. Zhou, and L. M. Duan, "Observation of a quantum phase transition in the quantum Rabi model with a single trapped ion," *Nat. Commun.* **12**(1), 1126 (2021).
10. K. S. Kumar, A. Vepsäläinen, S. Danilin, and G. S. Paraoanu, "Stimulated Raman adiabatic passage in a three-level superconducting circuit," *Nat. Commun.* **7**(1), 10628 (2016).
11. A.-G. Paschke, G. Zarantonello, H. Hahn, T. Lang, C. Manzoni, M. Marangoni, G. Cerullo, U. Morgner, and C. Ospelkaus, "Versatile control of $^9\text{Be}^+$ ions using a spectrally tailored UV frequency comb," *Phys. Rev. Lett.* **122**(12), 123606 (2019).
12. D. Hayes, D. N. Matsukevich, P. Maunz, D. Hucul, Q. Quraishi, S. Olmschenk, W. Campbell, J. Mizrahi, C. Senko, and C. Monroe, "Entanglement of atomic qubits using an optical frequency comb," *Phys. Rev. Lett.* **104**(14), 140501 (2010).
13. W. C. Campbell, J. Mizrahi, Q. Quraishi, C. Senko, D. Hayes, D. Hucul, D. N. Matsukevich, P. Maunz, and C. Monroe, "Ultrafast gates for single atomic qubits," *Phys. Rev. Lett.* **105**(9), 090502 (2010).

14. R. Islam, W. C. Campbell, T. Choi, S. M. Clark, C. W. S. Conover, S. Debnath, E. E. Edwards, B. Fields, D. Hayes, D. Hucul, I. V. Inlek, K. G. Johnson, S. Korenblit, A. Lee, K. W. Lee, T. A. Manning, D. N. Matsukevich, J. Mizrahi, Q. Quraishi, C. Senko, J. Smith, and C. Monroe, "Beat note stabilization of mode-locked lasers for quantum information processing," *Opt. Lett.* **39**(11), 3238–3241 (2014).
15. J. Mizrahi, C. Senko, B. Neyenhuis, K. G. Johnson, W. C. Campbell, C. W. S. Conover, and C. Monroe, "Ultrafast spin-motion entanglement and interferometry with a single atom," *Phys. Rev. Lett.* **110**(20), 203001 (2013).
16. M. Cetina, L. Egan, C. Noel, M. Goldman, D. Biswas, A. Risinger, D. Zhu, and C. Monroe, "Control of transverse motion for quantum gates on individually addressed atomic qubits," *PRX Quantum* **3**(1), 010334 (2022).
17. Y. Zhao, S. Wang, W. Zhuang, and T. Li, "Raman-laser system for absolute gravimeter based on ^{87}Rb atom interferometer," *Photonics* **7**(2), 32 (2020).
18. P. Cheinet, F. Pereira Dos Santos, T. Petelski, J. Le Gouët, J. Kim, K. T. Therkildsen, A. Clairon, and A. Landragin, "Compact laser system for atom interferometry," *Appl. Phys. B* **84**(4), 643–646 (2006).
19. J. B. Naber, J. Vos, R. J. Rengelink, R. J. Nusselder, and D. Davtyan, "Optical techniques for rydberg physics in lattice geometries," *Eur. Phys. J. Spec. Top.* **225**(15-16), 2785–2816 (2016).
20. M. Shahriar, A. Turukhin, T. Liptay, Y. Tan, and P. Hemmer, "Demonstration of injection locking a diode laser using a filtered electro-optic modulator sideband," *Opt. Commun.* **184**(5-6), 457–462 (2000).
21. H. B. Xue, Y. Y. Feng, X. J. Wang, S. Chen, and Z. Y. Zhou, "Note: Generation of raman laser beams based on a sideband injection-locking technique using a fiber electro-optical modulator," *Rev. Sci. Instrum.* **84**(4), 046104 (2013).
22. A. C. Wilson, C. Ospelkaus, A. P. VanDevender, J. A. Mlynek, K. R. Brown, D. Leibfried, and D. J. Wineland, "A 750-mw, continuous-wave, solid-state laser source at 313 nm for cooling and manipulating trapped $^9\text{Be}^+$ ions," *Appl. Phys. B* **105**(4), 741–748 (2011).
23. J. Mielke, J. Pick, J. A. Coenders, T. Meiners, M. Niemann, J. M. Cornejo, S. Ulmer, and C. Ospelkaus, "139 GHz UV phase-locked raman laser system for thermometry and sideband cooling of $^9\text{Be}^+$ ions in a penning trap," *J. Phys. B: At., Mol. Opt. Phys.* **54**(19), 195402 (2021).
24. P. J. Lee, B. B. Blinov, K. Brickman, L. Deslauriers, M. J. Madsen, R. Miller, D. L. Moehring, D. Stick, and C. Monroe, "Atomic qubit manipulations with an electro-optic modulator," *Opt. Lett.* **28**(17), 1582–1584 (2003).
25. J. Wang, K. Zhang, Y. Ge, and S. Guo, "Efficient frequency doubler of 1560nm laser based on a semi-monolithic resonant cavity with a ppktp crystal," *Opt. Commun.* **369**, 194–198 (2016).
26. D. Patel, V. K. Singh, and U. Dalal, "On the effect of the extinction ratio and the modulation index on optical up conversion using dsbsc modulation and transmitting over different fiber links," *Optik* **127**(24), 11845–11853 (2016).
27. Y. Fu, X. Zhang, B. Hraimel, T. Liu, and D. Shen, "Mach-zehnder: A review of bias control techniques for mach-zehnder modulators in photonic analog links," *IEEE Microwave Magazine* **14**(7), 102–107 (2013).
28. S. Shi, J. Yuan, Q. Huang, C. Shi, X. Luo, S. Lu, P. Yuan, H. Yu, and Q. Yue, "Bias controller of mach-zehnder modulator for electro-optic analog-to-digital converter," *Micromachines* **10**(12), 800 (2019).
29. S. Olmschenk, K. C. Younge, D. L. Moehring, D. N. Matsukevich, P. Maunz, and C. Monroe, "Manipulation and detection of a trapped $^{171}\text{Yb}^+$ hyperfine qubit," *Phys. Rev. A* **76**(5), 052314 (2007).
30. R. He, J.-M. Cui, R.-R. Li, Z.-H. Qian, Y. Chen, M.-Z. Ai, Y.-F. Huang, C.-F. Li, and G.-C. Guo, "An ion trap apparatus with high optical access in multiple directions," *Rev. Sci. Instrum.* **92**(7), 073201 (2021).
31. M. Qiao, Y. Wang, Z. Cai, B. Du, P. Wang, C. Luan, W. Chen, H.-R. Noh, and K. Kim, "Double-electromagnetically-induced-transparency ground-state cooling of stationary two-dimensional ion crystals," *Phys. Rev. Lett.* **126**(2), 023604 (2021).
32. L. Feng, W. L. Tan, A. De, A. Menon, A. Chu, G. Pagano, and C. Monroe, "Efficient ground-state cooling of large trapped-ion chains with an electromagnetically-induced-transparency tripod scheme," *Phys. Rev. Lett.* **125**(5), 053001 (2020).
33. T. P. Harty, D. T. C. Allcock, C. J. Ballance, L. Guidoni, H. A. Janacek, N. M. Linke, D. N. Stacey, and D. M. Lucas, "High-fidelity preparation, gates, memory, and readout of a trapped-ion quantum bit," *Phys. Rev. Lett.* **113**(22), 220501 (2014).
34. M. R. Dietrich, N. Kurz, T. Noel, G. Shu, and B. B. Blinov, "Hyperfine and optical barium ion qubits," *Phys. Rev. A* **81**(5), 052328 (2010).