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An integrated laser system for manipulating trapped ions qubits

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ABSTRACT

In experiments with atomic qubits encoded in the hyperfine levels of cold atoms or ions, the generation and control of multiple laser frequencies are often required for laser cooling and qubit manipulation. In this work, we demonstrate a laser system that integrates laser cooling, qubit initialization and detection, and Raman operations into a single setup, utilizing fiber laser technology and nonlinear optics. Specifically, a 369 nm laser for preparing and detecting $^{171}\text{Yb}^+$ ions, and a 554 nm laser for qubit Raman manipulation, are generated by modulating a seed laser at 1108 nm through a fiber electro-optic modulator (EOM), amplified by a Yb-doped fiber amplifier, and then converted to 369 nm and 554 nm using two sequentially placed periodically-poled nonlinear crystals. This method offers significant flexibility and scalability, as different laser frequencies can be generated by adding specific radio-frequency signals to the electronic system, without altering the optical setup. The switching time between laser frequency channels is measured at 6.5 ns. With a modulation bandwidth of 20 GHz, this approach can accommodate the hyperfine splittings of various ion species. Overall, This scheme optimizes the optical configuration for atom and ion operations, minimizes insertion losses, and provides an efficient multi-channel laser frequency generation solution, making it highly beneficial for atomic and ionic quantum information experiments.

1. Introduction

In quantum computation systems based on cold atoms and ions [1–5], quantum states are typically encoded in the hyperfine energy levels [6–8]. Operations on the atom and ion qubit, including Doppler cooling [9,10], qubit initialization, detection [11–13] and qubit manipulation, are carried out on these hyperfine energy levels. These operations are typically achieved by using laser within the same wavelength range and applying electro-optic modulators (EOMs) to generate laser sidebands that match the hyperfine energy level splitting [14–16]. The hyperfine energy level splittings of the qubit states in most atoms or ions occur in the GHz range. Traditionally, this process involves splitting the main laser into multiple beams, modulating each beam with an EOM respectively or using multiple EOMs in series [16,17]. Multiple optical components will lead to increased optical losses and lower spatial utilization efficiency, the stability of the entire optical path will also decrease. The use of wide-band fiber EOMs to flexibly generate multiple laser frequencies has been explored in recent years [8,18,19]. However, multi-frequency laser generation in the near ultraviolet (NUV) range, often required for trapped ions, is still not realized with wide-band

fiber EOMs. Furthermore, to coherently manipulate the hyperfine qubit of the trapped ion, an additional multi-tone laser system with a large detuning is required to perform the Raman operation on the qubit.

In this work, we present an integrated and robust solution that combines fiber laser optics with nonlinear processes. By utilizing a wide-band fiber electro-optic modulator (EOM) for multi-frequency modulation and two nonlinear crystals for third harmonic generation (THG), we achieve a switchable multi-frequency near-ultraviolet (NUV) laser at 369 nm [20,21], as well as a multi-tone laser at 554 nm for Raman operations. While wide-band fiber EOMs currently available are mainly focused in the infrared band unless a specific type of electro-optic material is employed [22,23]. The energy level transitions between the ground and excited states in many experimental alkaline earth metal ions, such as $^{40}\text{Ca}^+$ [24,25], $^{171}\text{Yb}^+$ [26,27], and $^9\text{Be}^+$ [28], typically occur in the ultraviolet band, with corresponding wavelengths of 397 nm, 369 nm, and 313 nm, respectively. To address this, we propose modulating an infrared laser (1108 nm) with a fiber EOM, followed by amplification using a ytterbium-doped fiber amplifier (YDFA).

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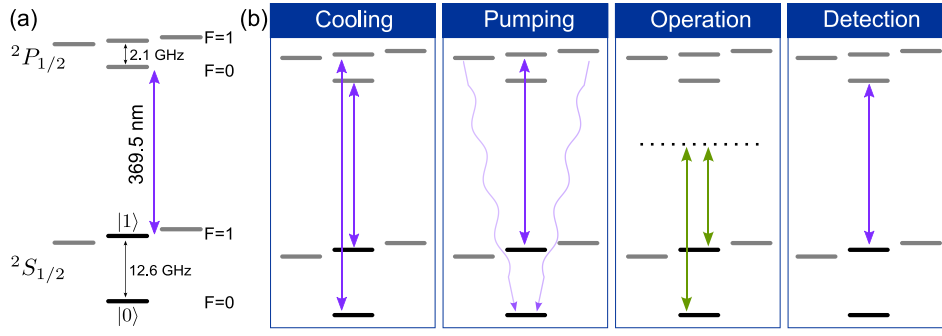


Fig. 1. Schematic diagram of energy levels and laser operation of a $^{171}\text{Yb}^+$ ion. (a) Energy levels of the ion, the qubit is encoded on $|0\rangle \equiv |^2S_{1/2}, F=0, m_F=0\rangle$ and $|1\rangle \equiv |^2S_{1/2}, F=1, m_F=0\rangle$. (b) Laser configuration for manipulating the ion, including stages of Doppler cooling, qubit pumping, stimulated Raman transition, and state readout, different lasers are required in different stages.

The amplified laser then passes through two periods of periodically-poled crystals to complete the THG process, generating the desired ultraviolet laser and its sidebands.

The laser system we proposed offers multiple advantages over systems that combine commercial NUV direct diode sources with multiple EOMs: (a) The amplified lasers are generated using fiber lasers and fiber amplifiers, ensuring high stability and avoiding mode hopping. (b) Both the modulation and amplification processes for laser generation use fiber connections, resulting in high-quality laser spots and excellent beam-pointing stability. (c) The modulation section offers greater scalability. When another laser frequency is required, it is only necessary to add a new RF channel instead of an additional spatial light EOM and its driving circuit. This approach reduces costs and improves space utilization. Since fiber seed lasers, fiber amplifiers, and broadband EOMs in the infrared band are commercially available and well-established, and the optics for THG utilize a single-pass optical path, which is also commercially available, the entire solution is easy to implement.

Stimulated Raman transition (SRT) [29,30] is a widely used method for coherently manipulating ion qubits. The laser system proposed in this work not only facilitates the simultaneous cooling, initialization, and state detection of ions in the NUV band, but also provides far-detuned Raman lasers in the visible (554 nm) [30,31] and infrared (1108 nm) bands. The amplified light with phase modulation, can be used to drive ion qubits after passing through a Mach-Zehnder interferometer or a dispersive optical element [8]. This Raman laser is particularly suitable for experiments involving hybrid ion-atom systems, as the beat frequency can be flexibly set [32,33]. Moreover, the wide-band frequency flexibility of our scheme offers more possible pathways for qubit manipulation, for example, frequency-chirped pulse lasers generated by an arbitrary waveform generator (AWG) can be used to achieve fast adiabatic Raman transfer in multi-level atomic or ionic states [34].

The laser modulation technique introduced in this work holds great potential for a wide range of applications. The characteristics of the wide-band electro-optic modulator can cover most of the hyperfine energy level differences of atoms and ions, making it suitable for use as an operating laser in most atom and ion quantum information experiments. In situations where modulation frequency switching is required, the modulation frequency can be quickly adjusted by applying a TTL-level signal to the control terminal of the RF switch circuit board. The experimentally measured switching time is approximately 6.5 ns.

In summary, this work significantly simplifies the optical path configuration of multi-channel modulated lasers in the NUV band, reduces optical path loss through electromagnetic methods, and preserves fast switching capabilities, one single optical path can complete multiple processes of ion operations, providing an excellent solution for modern atomic and trapped-ion quantum information experiments.

2. Scheme and experimental setup

The ion we utilize in this work is the $^{171}\text{Yb}^+$ ion, with its ground and excited state energy level diagrams illustrated in Fig. 1(a). The laser with a wavelength of 369 nm serves as the primary laser we require. The ground state hyperfine energy levels $|0\rangle$ and $|1\rangle$ are encoded as qubits utilized in quantum computation. The primary operational process of $^{171}\text{Yb}^+$ ions in quantum information experiments is depicted in Fig. 1(b) [17]. During the Doppler cooling process, besides the main laser, we also require a blue detuned laser with a frequency of 14.7 GHz to pump ions that have fallen into a dark state back into the cooling cycle. For the state pumping process, we employ a blue detuned 2.1 GHz laser to prepare the ions in the $|0\rangle$ state. For the state detection process, we do not require any additional sidebands and can accomplish it solely with the 369 nm main laser. For coherently manipulating the qubit with the SRT, we can use a multi-tone laser in the visible wavelength range [30,31].

Modulating the laser through the fiber EOM enhances the flexibility and scalability of the entire process. To meet laser modulation requirements that are not within the same time slots and at varying frequencies, we can conveniently add corresponding frequency signals and strategically plan radio frequency (RF) switches on the RF circuit board, ultimately inputting them into the fiber EOM for modulation. This approach converts traditional multi-channel optical switches into multi-channel electrical switches, significantly reducing power loss of the optical path while enhancing its stability.

The overall optical path diagram used in the experiment is shown in Fig. 2. The fiber EOM phase modulator, with a modulation bandwidth of 20 GHz, is the key component. A 1108 nm laser (Precilasers, FL-SF-1108-S, output power 100 mW, tunable range 6 GHz) with linear polarization is coupled into the EOM for modulation. The laser spectrum before and after modulation (at points A and B, respectively) is shown in Fig. 2(a).

Fig. 2(b) shows the electronics configuration we have implemented at the RF input terminal of the fiber EOM. A multi-channel RF signal generator generates RF signals with frequencies of 2.1 GHz, 12.6 GHz, and 14.7 GHz respectively. Each channel of signal generator is connected to a single pole double throw RF switch (ADRF5027, 9 kHz-44 GHz, insert loss ≤ 2 dB, isolation ≥ 51 dB) called SW1 and SW2 firstly, and then the outputs are successively connected to a single pole four throw RF switch SW3 (ADRF5046, 100 MHz-44 GHz, Insert loss ≤ 2.1 dB, isolation ≥ 46 dB) and a single pole double throw RF switch SW4 (ADRF5027), each RF switch features a control terminal for managing the direction of its opening and closing. Finally, the selected RF signal is input to the RF input port of the EOM through a wide-band RF amplifier (Minicircuits, ZVA-213-S+, 1-18 GHz, Gain ≥ 30 dB, P1 dB ≥ 14 dBm). The special design of the three-layer RF switch ensures that, while providing a sufficient number of RF channels, each RF signal maintains a sufficiently high degree of isolation (> 90 dB) from the

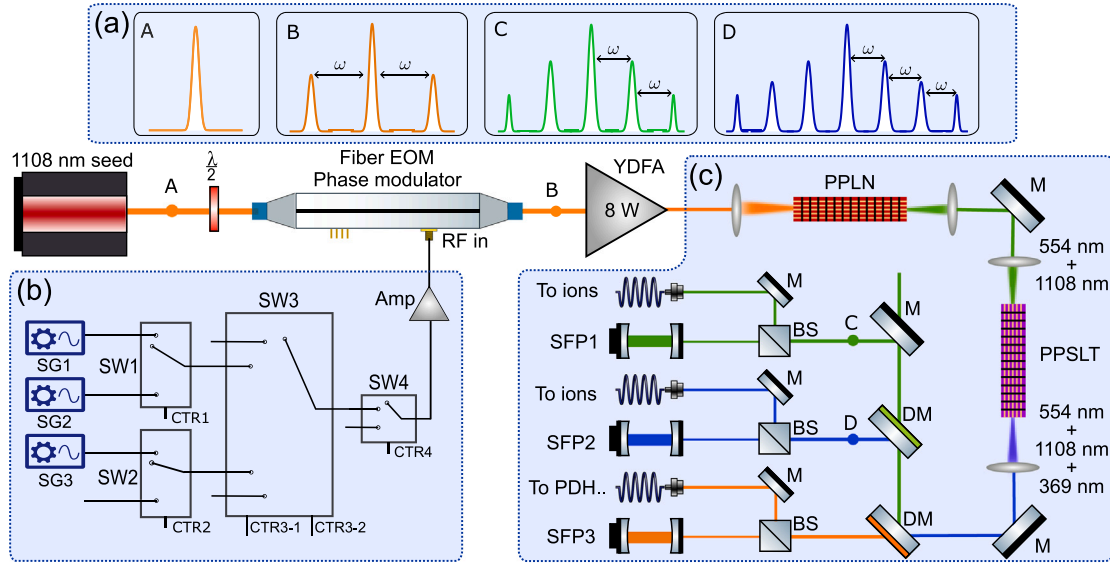


Fig. 2. Schematic diagram of the experimental laser path. (a) Schematic diagram of the spectrum at four different positions marked A-D. (b) The modulating electronics at radio frequency. (c) Part of the nonlinear optical frequency conversion, the laser spectrum is measured by Scanning Fabry-Pérot Cavities (SFPs). SG: Signal Generator, SWx: xth Radio Frequency Switch, YDFA: Ytterbium-Doped Fiber Amplifier, L: Lens, M: Reflecting Mirror, DM: Dichroic Mirror, OC: Optic Coupler.

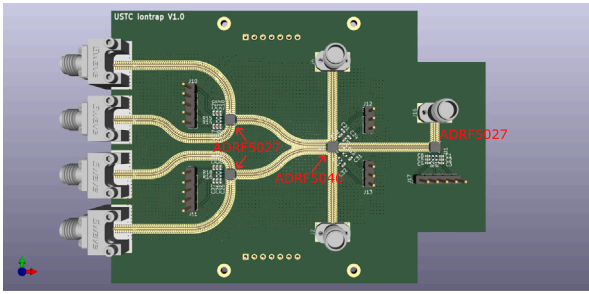


Fig. 3. A designed radio frequency (RF) circuit board. The board includes four main RF switch chips and seven input external interfaces, the control and power interfaces are led out through 2.54 mm pins.

others. This prevents unwanted frequency components from appearing in the output spectrum of the 369 nm laser. Such a design is conducive to reducing the error rate during qubit operations and enhancing the fidelity of state preparation and measurement (SPAM).

We have designed and made a high-frequency circuit board for this purpose, as shown in Fig. 3. The circuit board mainly consists of four RF switch chips and seven input SMA interfaces. The circuit board uses Rogers RO4003C as the material, with a dielectric loss of 0.0027, and crimped solderless SMA connectors, effectively reducing the insertion loss of RF signals transmitted on the board. In addition, the control line of the RF switch is led out through 2.54 mm pins, making it easy to connect with external control signals. Through multiple tests, under the frequency of 14.7 GHz, insert loss and isolation are 9.1 dB and 105 dB of the board. Under the premise of ensuring sufficient isolation, the fidelity of ion qubit SPAM is guaranteed.

We used a programmable pulse generator (Spincore, pulse-Blaster-ESR-PRO) to control the RF switches SW1-SW4. By altering the pulse width of the TTL signal, we can achieve timing control over the modulation frequency of the laser, thus enabling precise manipulation of qubits. The 1108 nm modulated laser output from the fiber coupler is amplified to 8 W by the YDFA (Precilasers, FA-SF-1108-10-CW). The amplified laser is then sequentially coupled into two periodically poled crystals to generate a 554 nm laser via the second harmonic generation (SHG) process, and a 369 nm laser via the THG process. The first nonlinear crystal, a Periodically Poled Lithium Niobate (PPLN),

converts the 1108 nm laser into a 1.2 W 554 nm laser, which can be used for the SRT operation. The 554 nm laser and the remaining 6.6 W of 1108 nm laser are then focused into the second nonlinear crystal, a Periodically Poled Stoichiometric Lithium Tantalate (PPSLT, Oxide Corporation, poling period 7.72 μm), through an aspherical lens, where a 369 nm laser with an output power of 15 mW is generated via a Sum-Frequency Generation (SFG) process. Due to the PPSLT being a periodically-poled phase-matching crystal with third-order, the SFG efficiency is not particularly high, which can be improved by optimizing the poling period in the future.

For input seed laser with amplitude E_0 and frequency ω_0 , the output laser after the fiber EOM can be expressed as [8]

$$E = E_0 \sum_{n=-\infty}^{+\infty} J_n(\beta) e^{j[(\omega_0+n\omega)t+n\varphi_0]} \quad (1)$$

where $\beta = \pi U_0 / V_\pi$ represents the modulation depth, U_0 is the RF signal amplitude, and J_n is the n 'th Bessel function. The output appears as a frequency comb in the frequency domain, with a frequency spacing of ω . The lasers with different frequencies then mix in the nonlinear crystals.

Under small modulation depth, mainly the carrier ($n = 0$) and first-order sidebands ($n = \pm 1$) contribute to the nonlinear processes of SHG and SFG to generate 554 nm laser. The photoelectric field of the carrier and sidebands are given by $E_{0,1108} = E_0 J_0(\beta) e^{j\omega_0 t}$ and $E_{\pm 1,1108} = E_0 J_{\pm 1}(\beta) e^{j[(\omega_0 \pm \omega)t + \varphi_0]}$, respectively. The amplitude and power of 554 nm laser can be expressed as follows:

$$E_{0,554} = k_{0,554} E_{0,1108}^2 + k_{1,554} E_{1,1108} E_{-1,1108} \quad (2)$$

$$= E_0^2 [k_{0,554} J_0^2(\beta) + k_{1,554} J_1(\beta) J_1(\beta)] e^{j2\omega_0 t}$$

$$P_{0,554} = |E_{0,554}|^2 \quad (3)$$

$$= E_0^4 [k_{0,554}^2 J_0^2(\beta) + k_{1,554}^2 J_1(\beta) J_1(\beta)]^2$$

where $k_{0,554}$ and $k_{1,554}$ are the proportional coefficients corresponding to the SHG and SFG parts, they are also related to the parameters of the crystal. Similarly, we can obtain the amplitude and power of the first-order sideband and second-order sideband of the 554 nm laser, the latter of which is obtained by the SHG of the first-order sideband of the 1108 nm laser. Using the same method, we can determine the amplitude and power of the SHG 369 nm laser after the PPSLT, taking

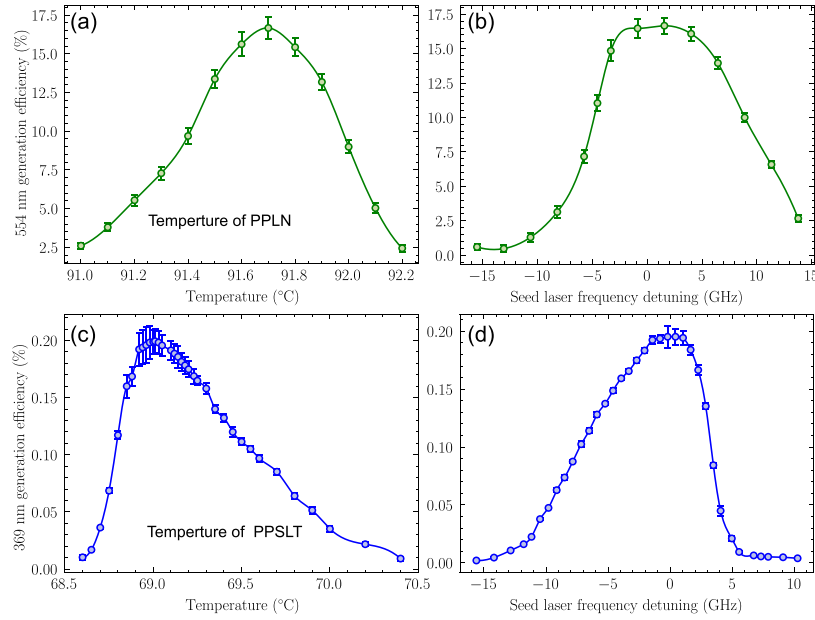


Fig. 4. Efficiency curves for second harmonic generation (a, b) and third harmonic generation (c, d) after two period-poled nonlinear crystals (PPLN and PPSLT), with varying crystal temperatures (a, c) and 1108 nm seed laser detuning (b, d), respectively. The data in (c, d) were obtained by setting the PPLN crystal to its maximum second harmonic generation temperature of 91.7 °C.

the 0th order as an example,

$$E_{0,369} = k_{0,369} E_{0,1108} E_{0,554} + k_{1,369} E_{1,1108} E_{-1,554} + k_{2,369} E_{-1,1108} E_{1,554} \quad (4)$$

$$= E_0^3 [k_{0,369} J_0^3(\beta) + k_{12,369} J_{-1}(\beta) J_0(\beta) J_1(\beta)] e^{j3\omega_0 t} \quad (5)$$

$$P_{0,369} = |E_{0,369}|^2$$

$$= E_0^6 [k_{0,369} J_0^3(\beta) + k_{12,369} J_{-1}(\beta) J_0(\beta) J_1(\beta)]^2$$

where $k_{12,369}$ is a constant coefficient re-combined from the last two terms in Eq. (4).

As evident from the formula above, both SHG and SFG redistribute the power among the sidebands of the laser. Consequently, the generated 369 nm laser acquires additional higher-order sidebands from the 1108 nm laser, which initially contains only low-order sidebands. As shown in Fig. 2(a), the 1108 nm laser, generated by the first-order sideband in the spectrum, undergoes two nonlinear processes, ultimately generating second- and even third-order sidebands on the 369 nm laser. To this end, we present the relative sideband intensities of three laser wavelengths at different modulation depths in the subsequent sections.

The efficiency of the SHG and SFG processes in both PPLN and PPSLT crystals primarily depends on the temperature of the crystals and the power of the pump laser. For the same seed laser frequency, we scanned the temperatures of the two nonlinear crystals and obtained their temperature-phase matching curves, as illustrated in Fig. 4(a,c). It is evident that when the pump laser power is 8 W, the optimal temperatures for SHG and SFG are 91.7 °C and 69.02 °C, respectively, with corresponding efficiencies of 17% and 0.2%. Subsequent experiments were conducted under these conditions.

Additionally, the bandwidth of the nonlinear crystals directly determines the intensity of each sideband component after laser modulation. Therefore, by tuning the laser frequency of the seed laser, we measured the frequency response of the two crystals under the optimal phase-matching temperature conditions described above, as shown in Fig. 4(b,d). From the figure, it is clear that the 3 dB bandwidths of the two crystals at the corresponding wavelengths are 28.8 GHz and 33.6 GHz, respectively. If we improve the SFG efficiency by using a PPSLT with a first-order poling period in the future, the corresponding bandwidth would decrease to one-third of the original value, i.e. 11.2 GHz. This reduction is not favorable for the generation efficiency of the sidebands for cooling laser.

The output laser contains three wavelengths: 1108 nm, 554 nm, and 369 nm, with each wavelength also including modulated sideband components. By using dichroic mirrors (DMs) for beam splitting, we finally obtain the 369 nm and 554 nm modulated laser beams, respectively. Finally, the lasers are coupled into the ion trap through polarization-maintaining fibers and the simple optical path configuration aids in improving the coupling stability.

3. Experiment results and analysis

To ensure the accuracy of the spectrum in the ion qubit operation experiment, each wavelength of the laser is coupled into a Scanning Fabry–Pérot (SFP) cavity for verification before being input into the ion trap. The spectra of the operating lasers required during the cooling, pumping, and readout of Yb ions are shown in Fig. 5, which presents the transmission spectrum generated by the modulation of radio frequency signals at different frequencies across three channels. The three different SFP cavities have varying transmittance and free spectral ranges for different wavelengths of laser, leading to differences in the linewidth and repetition period of sidebands in the spectra of different wavelengths.

In this experiment, the focus is on the power of the main peak and its sidebands in the output laser after nonlinear processes. By comparing Fig. 5(c,e), it is evident that due to the bandwidth limitation of the crystal in the EOM, sidebands of the same order but with higher frequencies can lead to lower sideband amplitudes. Comparing Fig. 5(a,b) and (c,d), we see that the seed laser with a lower modulation frequency and smaller sideband amplitude results in a larger sideband amplitude after the THG, indicating that the bandwidth of the nonlinear crystal has a more pronounced effect on the sideband amplitude.

By exploiting the bandwidth characteristics of the nonlinear crystals, we can adjust the amplitude ratio of the outgoing laser sidebands, as shown in Fig. 5(f). By adjusting the temperature of the nonlinear crystal, we can set the amplitudes of the main sideband and the positive first-order sideband in the 554 nm laser to be equal, while the amplitude of the negative first-order sideband decreases. In this case, the nonlinear crystal functions as an optical filter [35].

To more intuitively demonstrate the difference in RF power required to generate sidebands with the same modulation depth before and after

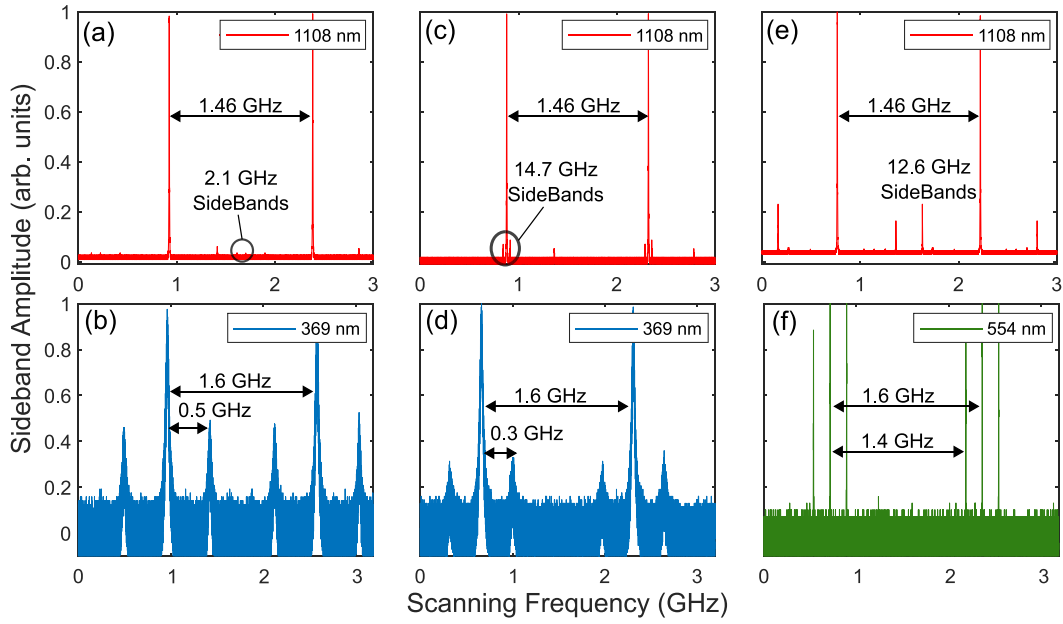


Fig. 5. The spectrum of the operating lasers required during the cooling, pumping, and operation of Yb ions under 3 kinds of RF settings. (a), (b) 2.1 GHz, -2.7 dBm. (c), (d) 14.7 GHz, 8 dBm. (e), (f) 12.6 GHz, 8 dBm.

the nonlinear process, we modulated the 1108 nm seed laser with a single 2.1 GHz frequency modulation signal. During the experimental process, we initially employed the SFP cavity to measure the carriers intensity of each laser wavelength at cavity resonance in the absence of RF signal. Subsequently, we scanned the intensity of the RF signal (P) within a specified range and measured the x -order sideband intensities $I_{x,\lambda}(P)$ ($x = 0, 1, 2$, $\lambda = 369$ nm, 554 nm, 1108 nm) of the output laser with 3 different wavelengths (λ). The ratio of $I_{x,\lambda}(P)$ to $I_{0,\lambda}(0)$ was defined as the relative intensity $R_{x,\lambda}(P)$ of the laser sidebands. A schematic diagram illustrating the relationship between the RF signal intensity and the relative intensity $R_{x,\lambda}(P)$ of each sideband is shown in Fig. 6. The coordinate points in the figure represent the measured values of each sideband, while the solid lines represent the fitting results of the theoretical formulas derived from processes similar to Eqs. (3) and (5). The experimental findings indicate that the modulation sideband amplitude of the output laser from this laser system is directly proportional to the RF power level. Notably, the nonlinear process reduces the RF power required to generate high-order sideband amplitudes in the output 369 nm laser. This observation aligns with our previous theoretical derivation and helps to lower the RF power requirements in quantum information experiments.

Next, we characterized the switching timing of the laser system. A typical timing sequence used in the operation of single-ion qubits is shown in Fig. 7(a). Five TTL-level signals are input to the control port of the RF switch, and four distinct operations require rapid switching of the control signals. These TTL-level signals are generated by a programmable pulse generator. A photodetector was placed at the output port of the 369 nm laser for measurement, and the signal during the transition from cooling to pumping is captured and shown in Fig. 7(b). The switching time of the 369 nm laser is approximately $t_2 - t_1 = 6.5$ ns, which is mainly limited by the rise time of the RF switches and the response time of the photodetector.

It is evident from the experimental results that the total signal intensity of the output laser varies before and after the modulation signal is switched. This variation is primarily due to the bandwidth limitation of the PPSLT crystal, which restricts the amplitude of each sideband signal. By appropriately adjusting the crystal temperature, we can alter the crystal's filter center to select various modulation frequencies in different conversion efficiencies. This adjustment ensures that

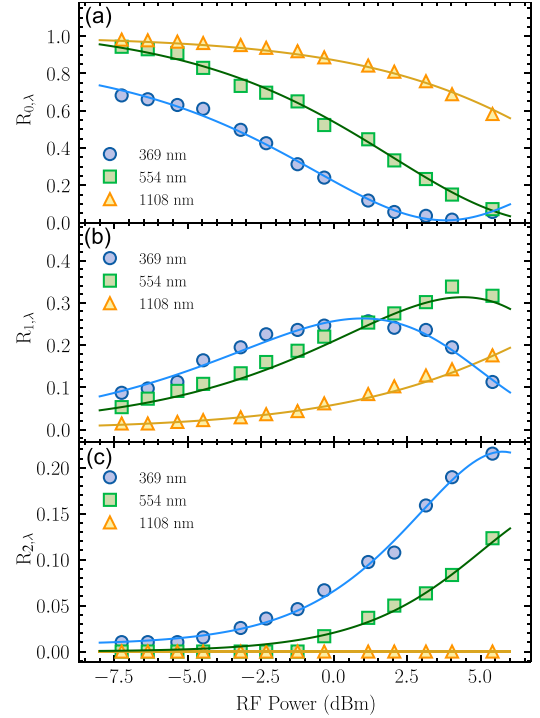


Fig. 6. The relative intensities of the sidebands for 369 nm, 554 nm and 1108 nm laser wavelengths under different RF power levels following phase modulation and THG. The solid line is the fitting result. (a) carriers (b) first order sidebands (c) second order sidebands.

the intensity of the output 369 laser remains relatively constant while switching the modulation state, provided there is a suitable ratio between the main laser amplitude and the sideband amplitudes. If needed, the total signal intensity of the output laser can be actively stabilized using an acoustic-optic modulator (AOM) or other methods [36,37].

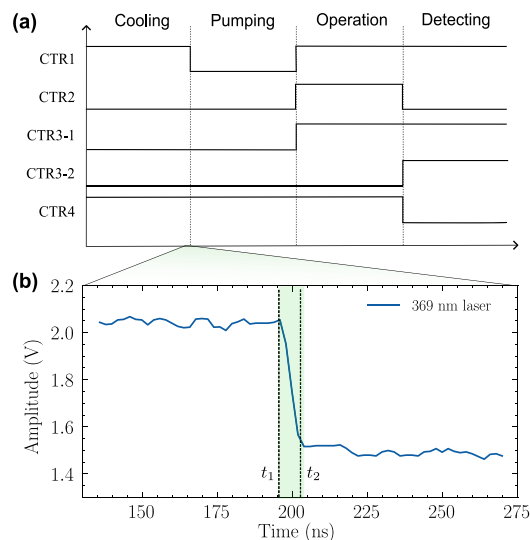


Fig. 7. (a) Timing sequence for the $^{171}\text{Yb}^+$ manipulation experiment. (b) The change in laser intensity during the transition from cooling to pumping indicates the switching time.

4. Summary and outlook

In this work, we proposed a wide-tunable, switchable modulated laser optical system at the NUV band based on a wide-band fiber EOM and a nonlinear THG. This system can be applied to lasers requiring external modulation at various frequencies and offers the advantage of simplifying the optical path. The system's total laser output THG efficiency can reach a peak of 0.2% after passing through the nonlinear crystals. Experimental results show that the frequency nonlinear effect effectively improves the utilization of RF signals, reduces optical loss, and provides optical filtering for sidebands of different modes. The optical switching time of the entire system is approximately 6.5 ns, which meets the switching time requirements for $^{171}\text{Yb}^+$ ion operation lasers. In summary, the multi-channel THG laser system proposed in this article boasts high integration, robustness, and scalability, offering an advanced solution for the configuration of ultraviolet lasers in atomic and ionic quantum information experiments. At present, even with a nonlinear crystal serving as an optical filter, it remains challenging to prevent the emergence of unwanted high-order sidebands using fiber EOM, but we noticed that the intensity of the second-order sideband is more than 20 dB lower than that of the carrier, thus barely affecting our application scenarios. In the future, there are still some methods to optimize the RF switchboard to reduce insertion loss and delay time, update the crystal's poling period, or optimize its temperature to further improve the laser's nonlinear conversion efficiency, thereby further improving system performance.

CRediT authorship contribution statement

Wei-Ran Ye: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jin-Ming Cui:** Writing – review & editing, Supervision, Methodology, Investigation. **Yan Chen:** Methodology. **Yi-Long Chen:** Methodology. **Rui-Rui Li:** Investigation. **Yun-Feng Huang:** Writing – review & editing, Supervision, Resources. **Chuan-Feng Li:** Supervision, Resources. **Guang-Can Guo:** Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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