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ABSTRACT

We demonstrate a novel laser frequency shift scheme using a 12-pass 350-MHz acousto-optic modulator (AOM). This AOM system shows better performance compared to ordinary acousto-optic modulation schemes. The frequency of the incident laser beam is shifted by 4.2 GHz with the total diffraction efficiency as high as 11%, and the maximum frequency shift is 5 GHz. Combining the ± 1 st order diffraction, laser signals with up to 10 GHz frequency difference can be obtained, which fulfill most frequency shift requirements of laser cooling and coherent manipulation experiments with alkali metal atoms.

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I. INTRODUCTION

Acousto-optic modulators (AOMs) play an important role in laser cooling, coherent manipulation of atoms,^{1–4} and other cold atom physics experiments, and they are usually used to modulate the frequency and intensity of lasers to switch the laser beams and to control the phase of lasers. AOMs get more and more favor due to their high efficiency, pure frequency spectrum, easy operation, and low cost. Most AOMs work mainly at the frequency band of 40–200 MHz, and their efficiency becomes poor when the driving frequency is as high as several GHz. To solve this problem, one usually uses electro-optic modulators (EOMs)^{5,6} or another diode laser⁷ to get high-frequency shifted lasers. However, the electro-optic modulation method is not conducive to eliminating the crosstalk of spatial overlapped high-order harmonics, while another diode laser is usually expensive and it needs a frequency stabilization system. Considering the needs of high efficiency and stable laser, it is necessary to invent a simple method to modulate and shift the laser frequency with the broad band by AOMs. There are two ways to enlarge the frequency shift range of an AOM. One way is to directly adopt a

high-frequency (\sim GHz) AOM. The commercial 3.4 GHz AOM is already available, but due to its low damage threshold and low efficiency (5%), the maximum output power one can get is comparatively low; this limits the usage of the AOM. Another way is to use the multi-pass AOM configuration. Besides the commonly used single-pass and double-pass AOM configurations, 3-pass, 4-pass, and 6-pass AOM configurations with ± 1 st order diffractions are used to shift the laser frequency up to 3 GHz.^{8–11} These techniques can fulfill the requirements of experiments using ⁶Li, ⁷Li, ²³Na, ³⁹K, ⁴⁰K, and ⁸⁵Rb atoms while they cannot fulfill the experiments using ⁸⁷Rb and ¹³³Cs atoms, whose frequency splittings are 6.8 GHz and 9.2 GHz, respectively. The frequency shift range, diffraction efficiency, and damage threshold of an AOM limit its application in some cold atom physics experiments, such as laser cooling dual-species ⁸⁵Rb and ⁸⁷Rb atoms. Here, we design and implement a new AOM frequency shifting scheme. By combining Faraday rotator–triangular prisms, polarization beam splitters (PBSs), and a usual 350-MHz AOM, we implement a 12-pass AOM frequency shifting and, thus, upgrade the frequency shift range of the AOM to 5 GHz. A 3-lens-collimation system is used to effectively decrease the divergence of a laser beam

and, thus, improve the diffraction efficiency of the AOM. The total diffraction efficiency is 11% when the driving frequency of the AOM is tuned to 350 MHz, and the output power of the +12th order side-band laser is 30 mW. The detuning range reaches 1.56 GHz with a total diffraction efficiency of 5.5%. We narrow the detuning range to 800 MHz and stabilize the diffraction efficiency to 4.5% as a lock point, and we have finally obtained a large-range frequency scanning system with the AOM. This is the first time to get laser signals with a total frequency difference up to 10 GHz via ± 1 st order diffractions with a single AOM. This technique also shows higher diffraction efficiency, higher damage threshold, and higher frequency shift range compared to other high range frequency shift techniques with the AOM.

II. EXPERIMENTAL DESIGN

In a multi-pass AOM configuration, a laser beam passes many times through an AOM and its frequency is shifted more; the total shift is $\omega = n\omega_0$, where ω_0 is the driving frequency of the AOM and n is the passing times. The more times the laser passes through the AOM, the more its frequency is shifted. To realize a practical multi-pass AOM system, we have several problems to solve: crosstalk between laser beams in different passing processes, poor diffraction efficiency, and the low damage threshold in the high-frequency shifting system with the AOM.

To keep the laser beams in each passing spatially separated, we fully use the polarization of the laser. With the PBS, quarter wave plate (QWP), and Faraday rotator, we get a 4-pass configuration. Since the AOM is insensitive to the vertical incident angle, we achieve a 3-pass configuration with triangle prisms. Combining these two configurations, we then achieve the 12-pass AOM system.

The first 3-pass P-polarization beams are diffracted in the vertical plane. The output beam of the third passing is reflected along the original path. The laser beam passes through a QWP twice, and its polarization is changed by 90° . The laser beams in the 4–6th passing are in S-polarization, and they are then reflected by using a PBS. A mirror next to the PBS is used to reflect the laser beam back to the AOM for another 6 passes, and laser beams in the 7–9th passing are in S-polarization, and those in the 10–12th passing are in P-polarization. After the 12th passing, the laser beam passes through the Faraday rotator and is reflected by using another PBS.

To improve the whole diffraction efficiency of the 12-pass system, we optimize the diffraction efficiency in each passing and adjust the divergence and size of the laser beam to match with the AOM. The single-pass efficiency is optimized to 90%. For our 780 nm laser beam with sub-millimeter beam size, the Rayleigh region is less than 1 m. We add one more lens to the former 2-lens configuration to ensure that the laser beam remains in the Rayleigh region during each diffraction process. The laser beam incident parallel to the AOM is focused by the first lens and then collimated by the second lens. After passing through the third lens, the laser beam is focused again. A mirror is placed at the focus of the third lens; when the laser beam is reflected by the mirror and passes through the third lens again, it becomes a parallel light beam. This design ensures that the laser beam remains parallel during each diffraction process. The first two lenses of the 3-lens system can compress the beam size and make it well match with the AOM.

The damage threshold of an AOM is mainly determined by light intensity and effective pass area. A typical commercial AOM has an intensity threshold of 10 W/mm^2 , while its effective pass area decreases quickly with the central frequency, so the damage

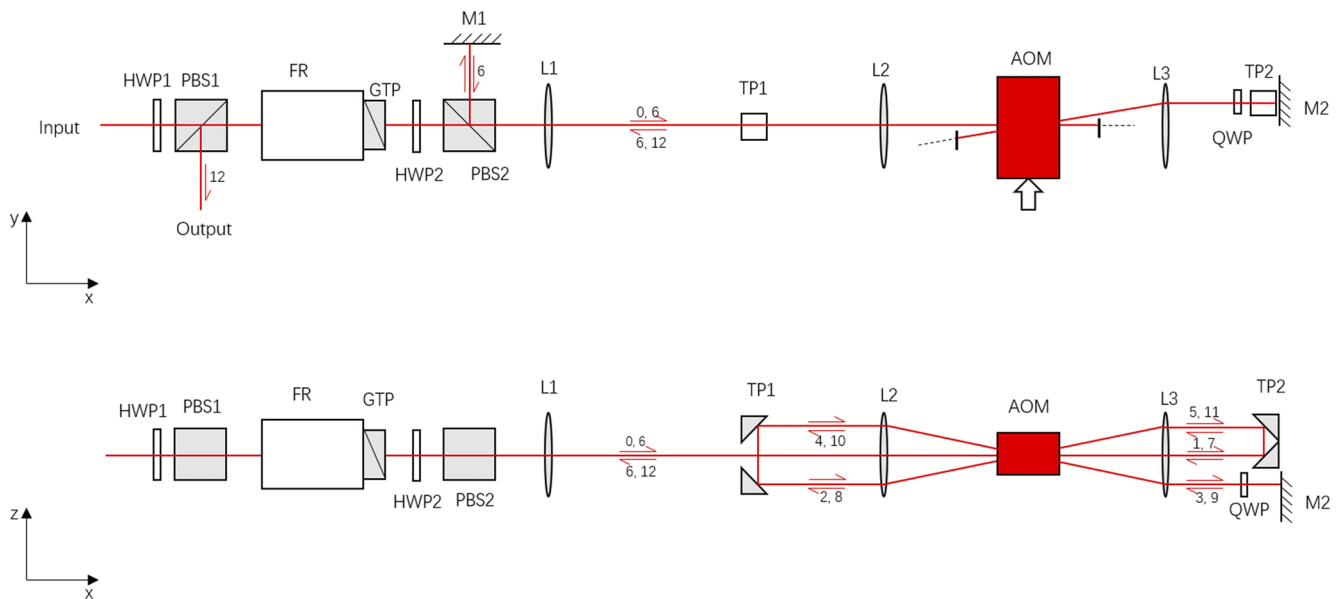


FIG. 1. Configuration of the 12-pass AOM system. PBS: polarization beam splitter; FR: Faraday rotator; HWP: half-wave plate; TP: triangular prism; QWP: quarter-wave plate; GTP: Glan–Taylor prism; and M: mirror. L: lens.

threshold of the high-frequency AOM is usually very low. Using a multi-pass AOM system is a good way to solve this problem, but the only question is how to choose the high-efficiency AOM. Most commercial 350 MHz AOMs have diffraction efficiencies of 40%–70% (MT350, AA optoelectronic) for 780 nm lasers. We use MT350, and the single pass efficiency is optimized to 90% in our 12-pass system.

The experimental setup is shown in Fig. 1. The linearly polarized laser beam is guided to an isolator via a single-mode polarization-maintaining fiber (PMF). The isolator consists of a PBS (PBS1), a Faraday rotator with 45°-rotation configuration, and a Glan–Taylor prism (GTP). The isolator allows the input beam to pass but isolates the inverted output beam such that the input laser beam is spatially separated from the output laser beam. After passing through another PBS (PBS2), the size of the input laser beam is reduced by the lens combination (L1, L2), and the focal lengths of L1 and L2 are 150 mm and 100 mm, respectively. The reduced beam sizes better match with the AOM aperture, thus improving the diffraction efficiency of the AOM. After the first passing, the +1st order diffraction beam of AOM is reflected by a triangular prism pair (TP2). The TP2 and the lens L3 form a cat's eye. Different from the cat's eye in the double-pass AOM scheme, here we use a triangular prism pair to separate the beam in the vertical direction. L2 and TP1 also form a cat's eye, where the two prisms are separated by a few millimeters in the vertical direction; this ensures the 0-order laser beam to pass through. Then, the diffracted beam, which passes through the AOM for the second time, is reflected to the AOM by the left cat's eye, and the third diffracted beam is reflected by the mirror (M2) below TP2. Thus, the laser beam sequentially completes the 4–6th diffraction. The QWP on the left side of M2 changes the polarization direction of the laser by 90°, and the 6th output beam of the AOM is reflected by PBS2 and the mirror (M1). Subsequently, the laser beam passes through the AOM for 7–12th time. The 12th diffracted beam (output beam) passes through the isolator and is output from PBS1.

III. PERFORMANCE

A. Main parameters

For a multi-pass AOM system, the total diffraction efficiency is one of the most important parameters. We define the total efficiency of the 12-pass AOM system as $\eta = P_{\text{out}}/P_{\text{in}}$, where P_{out} is the power of the output laser (the twelfth diffraction laser) and P_{in} is the power of the input laser. The value of η depends on the diffraction efficiency of the AOM and the transmittance of each component, and the key point of the high total efficiency is to improve the diffraction efficiency in each time.

The wavelength and output power of the seed laser (DL Pro, TOPTICA Photonics) are 780 nm and 90 mW, respectively. A part of the seed laser (30 mW) is coupled and delivered via the PMF to the 12-pass AOM system. The transmission efficiency of the isolator configuration is 80%, and the power of the input laser beam in the diffraction area is 24 mW. In this 12-pass AOM system, the first three processes for laser passing through the AOM can be independently optimized, while the 4–6th pass processes are the reverse processes of the first three times, and the 7–12th pass processes are repetitions of the previous 6 times. The efficiency of the first passing is optimized by adjusting the position and the angle of the AOM.

Thanks to the good matching between the beam size and the aperture of the AOM, the efficiency of the first pass is optimized to 90%. The efficiency of the second passing and the third passing is adjusted by TP1 and TP2, separately. The matching between the laser beam and the AOM, and the efficiencies of the second and the third passing are better than the first passing. Even if there is power loss caused by the prisms and lenses, the total efficiency of the first three passes is 73%. The diffraction efficiencies of the 4–6th passes are adjusted by M2. Due to the misalignment, the diffraction efficiencies of the 4–6th passes are lower than those of the first three passes, and the total efficiency of the 6 passes is about 45%. The 7–12th passes also show a lower efficiency less than 45%, and a total efficiency of 11% and an output power of 3.4 mW are obtained. Considering the power loss due to optics, the diffraction efficiency of the AOM for the 12-pass system is higher than 11%. The frequency of the input laser is shifted totally by 4.2 GHz when the AOM works at 350 MHz. The amount of frequency shift can be adjusted by scanning the driving frequency of the AOM. We scan the driving frequency from 280 MHz to 420 MHz and optimize the system at each frequency point to obtain the best diffraction efficiency. The experimental results are shown in Fig. 2. The matching between the AOM and the laser in the 12-pass AOM system is affected by many components, so it is hard to get a smooth curve when adjusting the system. The total diffraction efficiency of the system exceeds 5.5% over the scan range of 285–415 MHz. Thus, we have a hand tuned the “bandwidth” to nearly 1.56 GHz, and the total frequency range of the system can reach about 5 GHz. We also test the –1st order diffraction beam in the 12-pass AOM system and obtained similar results. Combined with the ± 1 order condition, we get laser signals with a total frequency difference up to 10 GHz.

The bandwidth is another important parameter of frequency shifting systems. For multi-channel systems, we expect the bandwidth of the AOM to increase by a corresponding multiple.

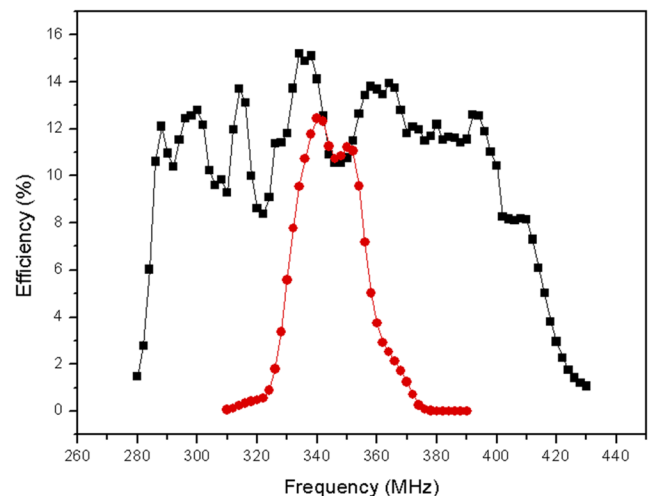


FIG. 2. The total efficiency of the 12-pass AOM system vs the driving frequency. The black squared line is the total efficiency after optimizing the system for each different frequency, and the red dotted line is the total efficiency for the system optimized at 350 MHz.

However, due to the misalignment of the laser beam, the total bandwidth often does not reach the expected value. We measured the bandwidth of the system at a center frequency of 350 MHz, as shown in Fig. 2; the 12-pass AOM has a total bandwidth of 300 MHz, and the corresponding single-pass bandwidth is 25 MHz (in contrast, the single pass bandwidth of the AOM given on the data sheet is 60 MHz.)

In cold atom experiments, lasers with different frequencies are applied to the atom system at a certain time sequence, which requires the laser frequency shifting module to switch quickly to avoid the crosstalk between different laser beams. We use a fast photodetector (PD) to monitor the intensity of the output laser over time and, thus, to measure the switching time of the AOM system. In the frequency shift keying (FSK) mode, the AOM drive frequency is switched between 350 MHz and 1 kHz so that the AOM system can be turned on and off. We measured the switch on time of 600 ns and the off time of 100 ns. As shown in Fig. 3, the switch-on time is slightly longer, which is caused by the delay of driving electrical components. In most cold atom experiments, the chronological control accuracy is in the order of milliseconds, and our system satisfies most of these conditions.

The output beam intensity of a multi-pass AOM system depends on the damage threshold and total diffraction efficiency of the AOM crystal. The AOM in our system has an optical power density of 10 W/mm², and the effective area is 0.5 mm². Considering the extreme case that the efficiency of each pass is always 90%, the damage threshold power of the input laser is calculated to be still higher than 300 mW. When the AOM operates near the center frequency (350 MHz), the total diffraction efficiency of the laser beam passing through the AOM 12 times is about 11%. Therefore, an output laser beam of 30 mW is easily obtained when the input laser beam is 300 mW, which is enough as a seed laser for a tapered amplifier (TA).

The frequency stability of a laser is very important for laser coherent manipulation experiments. The frequency stability of an AOM frequency shifting system is typically measured using a beat

signal between the input and the output laser beam. Here, we use an analyzer (Agilent technologies, N9030A) to analyze the beat signal of our 12-pass AOM system driven by a 350 MHz signal. As shown in Fig. 4, the obtained beat signal has a bandwidth of 4 Hz with almost no frequency transfer error and the system has an isolation of 22 dB. The main sideband of the 6-pass diffracted beam appears in the spectrum, which is caused by the non-ideal laser polarization and Faraday rotator.

B. Improvements

The bandwidth of the multi-pass AOM system is limited by the diffraction angle-based efficiency. The interaction between the laser beam and the AOM is Bragg scattering. The +1st order diffraction angle for the beam is approximated as

$$\sin \theta = \frac{\Omega \cdot v_L}{\omega \cdot v_s}, \quad (1)$$

where θ is the diffraction angle of the AOM crystal, Ω is the driving frequency of the AOM, ω is the laser frequency, v_L is the speed of light in the air, and v_s is the speed of sound in the crystal. When the driving frequency is swept, the diffraction angle follows. In the single pass condition, it is not a problem. While for the multi-pass AOM system, the laser passes through the AOM for many times, and the output laser beam of the previous pass is the input beam for the next pass, so the change of diffraction angle accumulates as well as the diffraction efficiency loss due to this change. To improve the bandwidth of the multi-pass AOM system, one needs to suppress the fluctuation of diffraction angle and efficiency. Here, we use an electric rotary table to enlarge the bandwidth of the system. We mount the AOM on the table and rotate the AOM in the horizontal plane to compensate the change of diffraction angle caused by frequency tuning and, thus, to optimize the diffraction efficiency. To stabilize

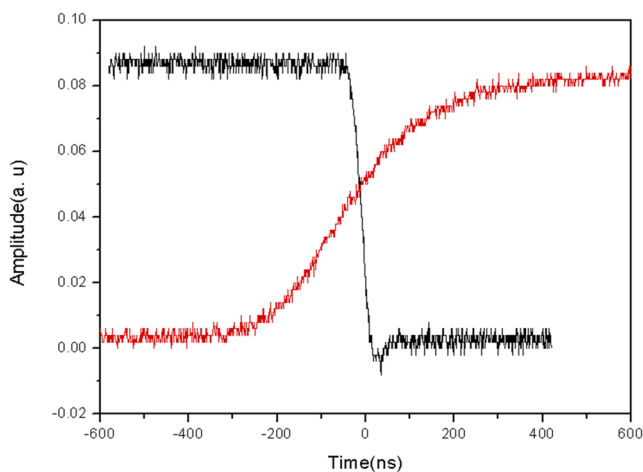


FIG. 3. Switch time for turning the AOM on (red line) and off (black line). Longer switch time for turning on may be due to the time delay of electrical components.

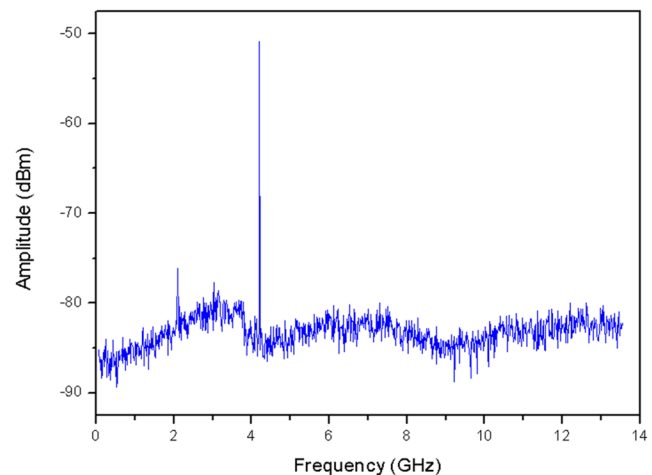


FIG. 4. Beat signal for 4.2-GHz frequency shifting. The 2.1-GHz sideband is due to the 6-pass diffraction beam. The isolation of the 12-pass system is 22 dB. The main reason for a low isolation is that the linear polarization of the laser beam is not ideal after 12-pass, and the isolation of PBS–Faraday rotator–GTP configuration is also not high.

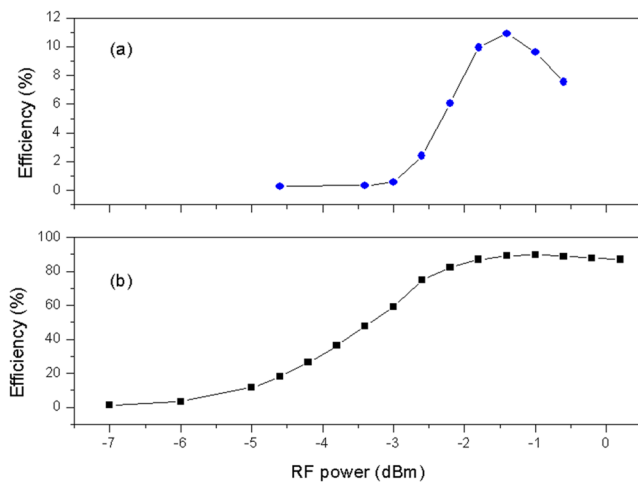


FIG. 5. The total efficiency of the 12-pass AOM system vs RF power. (a) The efficiency of the 12-pass AOM. (b) The efficiency of single pass AOM system. The RF power is only the output power of the local oscillator. The power stabilization system works in the region from -3 dBm to -1.5 dBm.

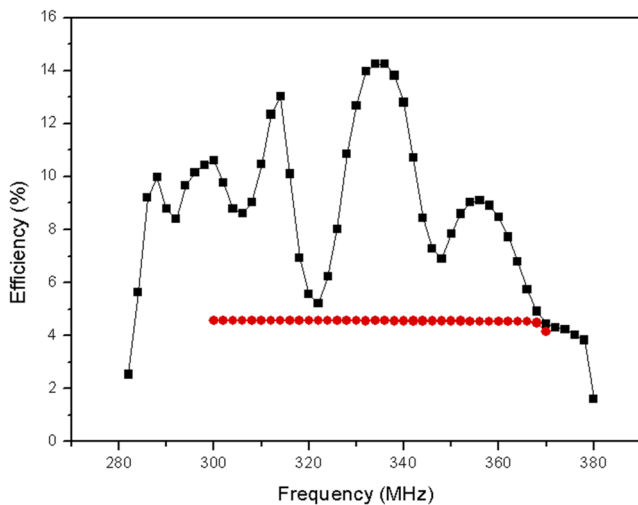


FIG. 6. Dependence of the total efficiency on the driving frequency. The black squared line represents the results without RF power stabilization, and the red dotted line represents the results with RF power stabilization.

the diffraction angle, we need to know the right position where the AOM should be for each different frequency. We first adjust the rotary table by hand when changing the frequency and get the best position where the system has the maximum diffraction efficiency. Then, we sweep the frequency and control the table with a LabVIEW program. The bandwidth of the single pass is 80 MHz, and the corresponding total bandwidth of 12-pass is enlarged to nearly 1 GHz (Fig. 5).

The fluctuation of the total efficiency is suppressed by applying a laser intensity stabilization at the output port of the system. The laser intensity stabilization system consists of a photodetector (PD), a home-made proportion integration differentiation (PID) module, and a voltage-controlled attenuator (VCA). A small part of the output laser beam is split and detected by the laser intensity stabilization. When the total efficiency of the 12-pass AOM system changes with the power of the driving RF signal, the PD, PID module, and VCA work as a feedback loop to control the radio frequency (RF) power. The lock point of the feedback loop can be set with the PID module. There is a valley near 320 MHz where the total efficiency is only 5%, so the lock point should be below that. We finally choose 4.5% as the lock point. Note that the lock point is, in fact, based on the power of the output laser. Here, our input power is 30 mW, so we lock the output power to 1.35 mW, and the result is also shown in Fig. 6. In the range of 300–370 MHz, the output power is stable for the 12-pass AOM system, and this means that the scanning range is 840 MHz.

IV. DISCUSSION

The 12-pass AOM system is a low-cost reliable method for frequency shift and sweep. It has better performance compared to other high-frequency shift techniques with AOMs. The main parameters of these techniques^{10–13} are listed in Table I.

The frequency stability of the output laser beam from the 12-pass AOM system is better than that of traditional frequency-locked diode lasers, so it perfectly satisfies the requirement of long-term and consecutive precision measurements, such as coherent acceleration of cold atoms, frequency chirp, atom clock, atom interferometer, and laser frequency modulation. This 12-pass AOM can be used as 4-pass, 6-pass, or 8-pass AOM system by adjusting some components (such as TP1 or Faraday rotator). With the help of two 8-pass AOM systems and two double-pass AOM systems, we built a laser system

TABLE I. Comparison of main parameters of AOM related techniques.

Affiliation	Technique/model	Efficiency (%)	Center frequency (GHz)	Bandwidth
CUHK ^a	4-pass AOM	30	1.6	~56 MHz
Universität Hannover	6-pass AOM	24	1.5	
Brimrose Corporation	TEF-1700-350	15	1.7	350 MHz
Brimrose Corporation	LnF-3500-1000	5	3.5	1 GHz
CETC ^a	PSG 1600-1	20	1.62	1.04 GHz
This work	12-pass AOM	11	4.2	300 MHz

^aCUHK: The Chinese University of Hong Kong, CETC: China Electronics Technology Group Corporation.

with only 1 seed laser and 5 TAs and realized a 2-isotope magneto-optical trap for a weak equivalence principle test.¹⁴ Such a laser system shows better stability and scalability than multi-seed laser systems. In the future, Faraday rotators with higher transmittance and AOM crystals with bigger apertures, higher diffraction efficiency, and broader bandwidth will be used to improve the performance of the system.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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