



Large-tuning-range frequency stabilization of an ultraviolet laser by an open-loop piezoelectric ceramic controlled Fabry–Pérot cavity

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Abstract: We demonstrate a laser frequency stabilization method with large tuning range to stabilize a UV laser by installing piezoelectric ceramic actuators into a Fabry–Pérot cavity with an ultra-low expansion spacer. To suppress piezoelectric drift, a two-layer symmetrical structure is adopted for the piezoelectric actuator, and a 14.7 GHz tuning range is achieved. The short-term drift of the piezoelectric ceramics caused by temperature and creep is eliminated, and the long-term drift is 0.268 MHz/h when the Fabry–Pérot cavity is sealed in a chamber without a vacuum environment. The long-term frequency drift is mainly caused by stress release and is eliminated by compensating the cavity voltage with an open loop. Without the need for an external reference or a vacuum environment, the laser frequency stabilization system is greatly simplified, and it can be extended to wavelengths ranging from ultraviolet to infrared. Owing to its simplicity, stability, and large tuning range, it is applicable in cold atom and trapped ion experiments.

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1. Introduction

Frequency-stable lasers are an essential element of experiments on cold atoms and trapped ions [1,2]. In these experiments, the drift of the laser central frequency must be far smaller than the natural line width of an atomic transition [3]. For the commonly used species $^{171}\text{Yb}^+$, the required cooling wavelength is in the ultraviolet (UV) band and the central frequency drift is below 1 MHz [4]. Traditionally, the UV laser source is produced by frequency-doubled process [5,6], meaning that there was an infrared beam available for locking to an infrared reference that achieve MHz level frequency stability, such as atomic or molecular vapor cells [7]. Recently, with the advent of UV diodes, cheaper lasers are available. However, for this kind of UV lasers, there exist relatively few suitable frequency references. Hence, Fabry–Pérot (FP) cavities are often used as a substitute frequency Ref. [8,9]. To stabilize the laser central frequency, additional stabilized frequency references are generally required to stabilize the length of the FP cavity. This will make the laser frequency stabilization system very complicated and difficult to maintain [10–12]. Therefore, a simple, stable laser frequency reference is vital for current atomic experiments.

In addition, a tuning range of the order of GHz is usually required in atomic experiments, owing to the hyperfine energy levels involved. This is not a serious problem for long wavelengths.

However, it becomes very challenging for short wavelengths as in the UV band, owing to the lack of suitable frequency modulation devices, such as electro-optic modulators (EOMs) and acousto-optic modulators (AOMs). Unfortunately, the cooling wavelengths of the rare-earth or alkaline-earth metal atoms or ions that are widely used in research on quantum information are often in the UV band. For example, $^{171}\text{Yb}^+$ [13,14], $^{40}\text{Ca}^+$ [15,16], and $^9\text{Be}^+$ [17,18] have cooling wavelengths of 369, 397, and 313 nm, respectively. Some progress has been made in achieving large tuning ranges. Tuning over a range of hundreds of MHz has been realized by using modulation transfer spectroscopy [19,20], a GHz tuning range by using atomic vapor and a transfer cavity [21], a 4 GHz range by using a pressure-tuned FP cavity [22], and a 5 GHz range at 420 nm by using a resonant optical feedback method [23]. The last of these is the maximum tuning range achieved at short wavelengths to date, but its optical lock can only remain for several hours. In our experiments, a 14.7 GHz tuning range is required, which used to bring the ion back to the cooling cycle [24,25], as shown in Fig. 1. So the tuning ranges available are far from meeting this need. Therefore, the above laser frequency stabilization method needs to be further optimized and improved for application in current atomic experiments.

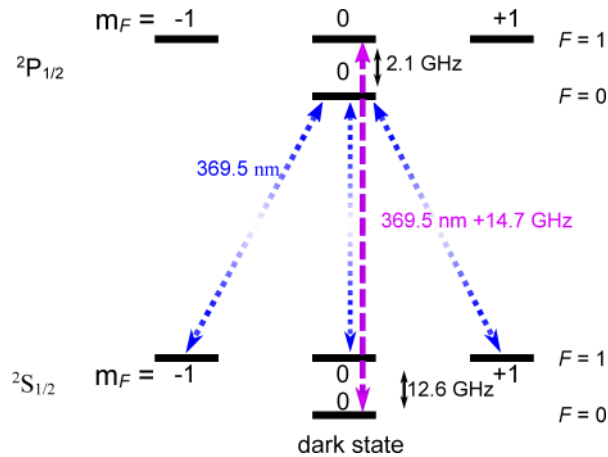


Fig. 1. Energy level scheme for $^{171}\text{Yb}^+$. The blue dotted line represent the cooling related level transitions. In the process of cooling, the ions will fall into the dark state with a certain probability and can not be cooled continuously, so a 14.7 GHz laser frequency is needed to bring the ions back into the cooling cycle, shown by the pink arrow.

In this letter, we demonstrate a simple and stable laser frequency stabilization method with large tuning range to stabilize a UV external cavity grating feedback diode laser (ECDL, Toptica, DL-PRO) using piezoelectric transducers (PZTs) in the FP cavity. In contrast to the traditional laser frequency method, arbitrary wavelength locking and a large tuning range can be achieved, without any need for an external reference or a vacuum environment. Although the length of a PZT experiences long-term drift (creep and temperature shift), the effect of this drift can be canceled out in principle if two layers of PZT are used such that their drifts are in opposite directions. Besides, the creeping drift of a PZT is characterized by an exponential decay with time, with a steady state being achieved within 0.1 s [26], and so the long-term drift will become smaller with time. Thus, the laser frequency can be stabilized very well. In our experiments, the ECDL radiation wavelength is 369.5 nm, and this is used to cool $^{171}\text{Yb}^+$. The cooling energy level linewidth is 20 MHz, and therefore the center frequency drift needs to be within 1 MHz.

2. Experimental setup

The structure of the two layers of PZT rings is shown in Fig. 2(a). They are stuck to a fused silica quartz (red in the figure) substrate, and the mirror is attached to the inner PZT ring. The other end of the outer PZT ring (blue) is bonded to the cavity [27] by the epoxy AB glue (Agilent, 9530001), and align their centers. As the PZT length drifts in the direction of stretching, the outer PZT makes the cavity longer, while the inner PZT (pink) makes the cavity shorter, and vice versa. Therefore, their drifts will be partially canceled out. The lengths of both PZTs are 15 mm, and the diameters of the outer and inner PZTs are 20 and 11 mm. The green component in the figure is the cavity mirror, with a reflectivity of 99%.

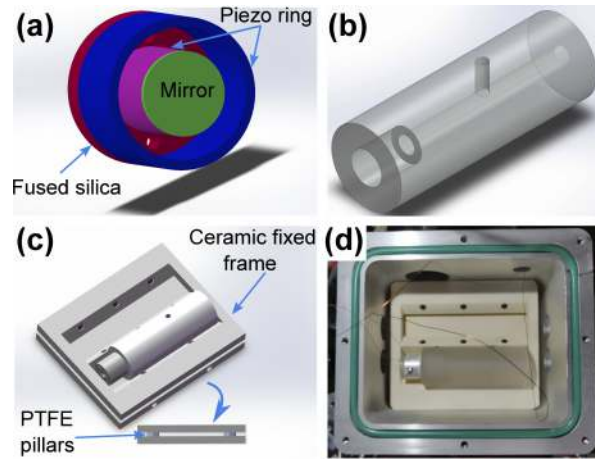


Fig. 2. Architecture of the FP cavity. (a) Two-layer structure of PZT rings, bonded to a fused silica substrate, to cancel out length drift. (b) ULE cavity structure, designed in a cylindrical shape for convenience of fixing. (c) Point-contact ULE cavity and ceramic support frame, to reduce heat transfer to the FP cavity (as explained in the text). Two FP cavities can be installed in the fixing frame. The lower picture shows a two-layer ceramic support structure, connected by PTFE pillars. (d) Internal structure of the chamber. For convenient temperature control and to avoid the impact of air convection, an aluminum chamber is used.

The spacer is made of an ultra-low-expansion glass (ULE, Corning 7972) with a length of 98.5 mm [~ 1.5 GHz free spectral range (FSR)], to minimize the effects of temperature fluctuations, as shown in Fig. 2(b). To simplify the cavity coupling, we use a hemispherical cavity (i.e., a cavity with one flat and one curved mirror). The radius of curvature is 100 mm, and the corresponding waist of the FP cavity is $37.8 \mu\text{m}$. The finesse of the FP cavity is 97, and hence the cavity linewidth is about 15 MHz.

The frequency stability of the FP cavity is affected by the temperature of the chamber, T :

$$\frac{\Delta T}{T} = \frac{\Delta n}{n} = \frac{\Delta L}{L} = \frac{\Delta \nu}{\nu}, \quad (1)$$

where n is the refractive index of the air in the chamber, L is the length of the FP cavity, ν is the resonant frequency of the FP cavity, and ΔT , Δn , ΔL , and $\Delta \nu$ are the respective changes in these quantities. In our experiment, the temperature fluctuates within 20 mK, which means that, according to Eq. (1), the frequency fluctuation is less than 0.09 MHz. In addition to the effect of temperature, changes in atmospheric pressure can also affect the refractive index n . However, according to the ideal gas law, we find that the influence of atmospheric pressure variations on the pressure in the chamber is negligible.

Considering that the coefficient of thermal expansion of ceramics is $\sim 7.7 \times 10^{-6}/\text{K}$, which contributes to the frequency fluctuations $< 1 \text{ kHz}$, and to further reduce heat conduction, we use a two-layer ceramic structure as the fixed frame, connected by polytetrafluoroethylene (PTFE) pillars, as shown in Fig. 2(c). Two wedge-shaped grooves and 1.2 mm deep holes are machined in the top ceramic, and PTFE balls of 2 mm diameter are put into the holes. The FP cavity is thus supported by point contact with the balls, and so the heat transferred to the cavity is further reduced. This structure also reduces the impact of vibration [28,29]. In our experiment, two FP cavities can be installed on the fixing frame, and this arrangement can be extended to accommodate multiple cavities by increasing the size of the ceramic fixing frame. Finally, to control the temperature and avoid air convection, we designed an aluminum chamber, the internal structure of which is shown in Fig. 2(d). The FP cavity is sealed in the chamber. The PZT electrode is connected via a feedthrough by copper wire.

The cavity coupling efficiency is measured to be $\sim 30\%$ in air, as shown in Fig. 3(a). The reason for the low coupling efficiency is the loss of the FP cavity.

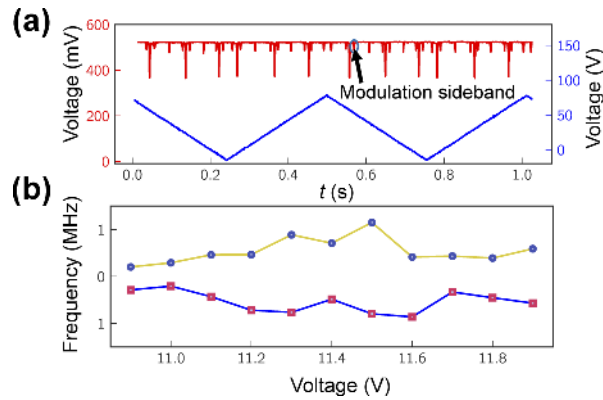


Fig. 3. (a) FP cavity coupling efficiency. The red line is the reflected signal of the cavity, and the blue line is the scanning signal of the inner PZT. The coupling efficiency is $\sim 30\%$. (b) PZT hysteresis. The maximum deviation of the frequency is measured at the same voltage six times. The gold line with circles represents the upper limit of the deviation and the blue line with squares represents its lower limit. The circles and squares are experimental data points.

A reference laser (the frequency of which is stabilized to another ultra-stable cavity such that the frequency fluctuation is less than 15 kHz/day) is employed for measuring the piezoelectric hysteresis effect [26]. The detailed steps are as follows. The voltage of the inner PZT (IT6133B, ITECH, ripple voltage $< 0.05\%$) is changed back and forth three times with the same start and stop voltage when the laser is locked, and the beat frequency with the reference laser is recorded. Then, the maximum deviation relative to the average frequency at the same voltage is found, the result is shown in Fig. 3(b). The time interval between adjacent points is more than 1 min. The maximum frequency deviation is about 2 MHz , although this can be further improved [30–32].

To measure the performance of the FP cavity and make the system simple and compact, we use a Red Pitaya 125-14 as a servo system. This has two input channels with 50 MHz bandwidth and two 14-bit analog-to-digital converters, which allows a high signal-to-noise ratio (SNR) to be obtained. It also possesses two output channels with 14-bit digital-to-analog converter. All four channels possess a 125 MS/s sample rate, and so the feedback loop bandwidth is enough for a PZT [33]. We use PyRPL software to stabilize the frequency.

A schematic of the frequency locking and measurement system is shown in Fig. 4. We use the Pound–Drever–Hall (PDH) technique to stabilize the frequency, which corresponds to the

IQ and lockbox module in PyRPL. The modulation signal is generated by the IQ module, and demodulation can also be completed in this module (for simplicity, we directly modulate the laser current at 7 MHz, because the free-space EOM is sensitive to temperature change in the UV wavelength). The feedback signal is then produced in the lockbox module by the demodulated signal. Fast feedback is used to feed back the laser diode current, and slow feedback is used to feed back the piezoelectric voltage in the laser [34]. For the PDH technique, a high SNR is required [35], and so a low-noise amplifier (LNA) is used to amplify the reflected signal from the photodetector.

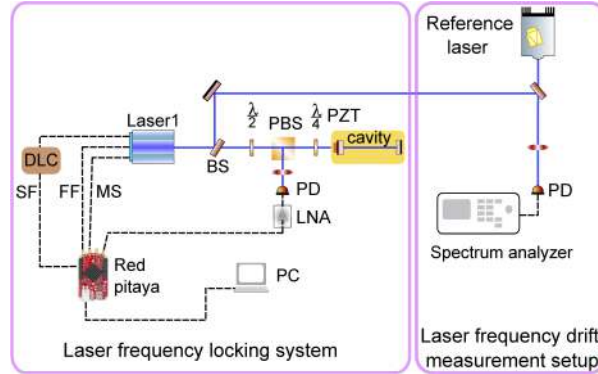


Fig. 4. Schematic of the frequency locking and measurement system. The left and right boxes are the laser frequency locking and laser frequency drift measurement systems, respectively. Laser1 is a UV ECDL (Toptica, DL-PRO). The frequency of the reference laser is stabilized to another ultra-stable cavity, and the frequency daily fluctuation is below 15 kHz. DM, dichroic mirrors; SM, silver mirror; DLC, digital laser control; BS, beam splitter; $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; PBS, polarized beam splitter; PD, photodetector; MS, modulation signal, with modulation frequency 7 MHz; FF, fast feedback signal; SF, slow feedback signal; PC, personal computer; LNA, low-noise amplifier; black dotted line, electrical signal; blue line, optical signal.

Part of the beam is reflected by the cavity directly, and, to avoid LNA saturation, there is a DC block (not shown in Fig. 4) between the photodetector and the LNA. We have measured the delay of the demodulation system to be ~ 1 ms, and so the feedback bandwidth is below 1 kHz. The delay is caused mainly by the communication between the computer and Red Pitaya.

3. Results and discussion

To evaluate the tuned performance of the FP cavity, we measured a series of beat frequencies by changing the voltage of cavity, the results is shown in Fig. 5. Meanwhile, in the process of laser cooling, the ions will fall into the dark state with a certain probability and can not be cooled continuously, so a 14.7 GHz laser frequency is needed to bring the ions back into the cooling cycle, as shown in Fig. 1. Therefore, the frequency of the laser is tuned to 14.7 GHz to excite ions out of the dark state. Compared with the fixed-point tuning (PM-Yb+_14.7, QUBIG) reference laser, with the same pump power, the cooling fluorescence counts both of them are same. This result shows that the tuning range is sufficient for the $^{171}\text{Yb}^+$ experiment. In fact, we believe that a larger tuning range can be achieved, but this would be difficult to measure experimentally because it would exceed the bandwidths of most detectors at UV wavelengths. This result will be of great significance for the laser with large mode-hop free tuning range, such as continuously tunable laser (CTL, Toptica) or [36–38].

The stability of the FP cavity is investigated by recording the beat frequency with the reference laser as shown in Fig. 4 when laser1 is locked. The result is shown in Fig. 6(a). The drift of the

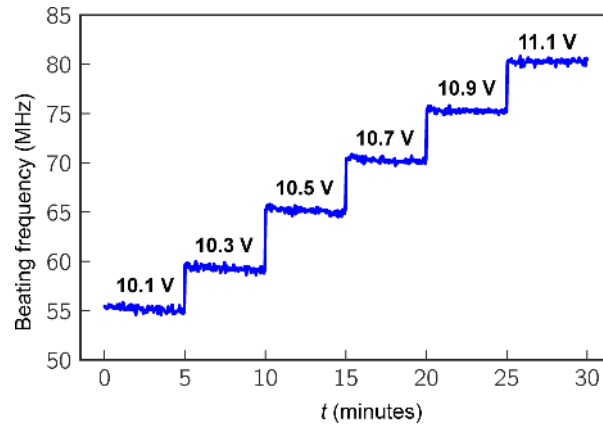


Fig. 5. The beating frequency by tuning the voltage of cavity and the measurement time at each voltage value is 5 minutes.

beat frequency is about 11 MHz over a period of 41 h, and so the velocity of frequency drift is 0.268 MHz/h, and the standard deviation of short-term fluctuations is below 0.6 MHz. This result is better than that reported in [3,4,21,39,40] and similar to the result with a transfer cavity [8].

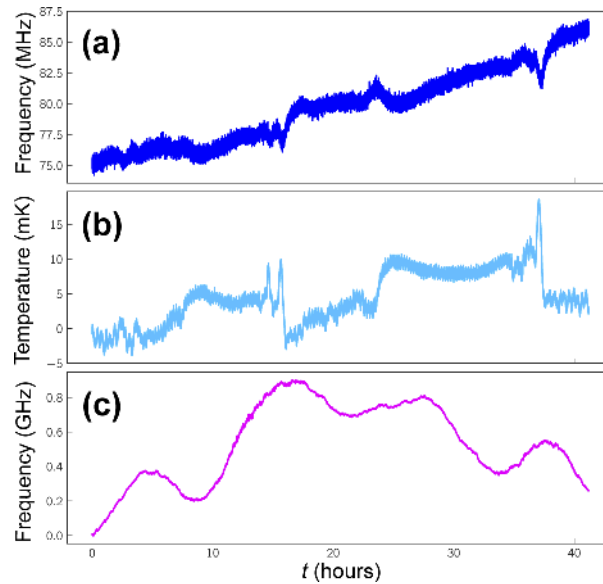


Fig. 6. Frequency stabilization with measurements over a period of 41 h. The frequency drift is 11 MHz. (a) Beat frequency with the reference laser. (b) Chamber temperature drift. (c) Compensated frequency drift of the UV laser.

From Figs. 6(a) and 6(b), one can infer that the effect of temperature on cavity length is limited: in Fig. 6(b), when the temperature fluctuates by 10 mK, the corresponding center frequency fluctuation in Fig. 6(a) is less than 1 MHz and when the temperature stabilizes to its previous value, the frequency still drifts in one direction. This result also shows that our thermal insulation design works well. In Fig. 6(a), we can see that the long-term drift velocity of the frequency has a linear relationship with time, which means that the main reason for this drift is not the creep of the PZT, because the creep has the form of an exponential decay [26]. Figure 6(c) shows

the compensated frequency drift of the laser. The maximum frequency compensation reaches 935.12 MHz, which shows that our servo system is very robust.

When the whole system reaches equilibrium, most of the volume of each supporting ball is confined to the hole in which it sits. Therefore, the direction of ball drift is perpendicular to the direction of the cavity length, and so the influence of the point contact balls can be ignored. In our experiment, the input optical power is 350 μW , and the variation of optical power is less than 5 μW , so the frequency change due to changes in optical power at about the 10^{-14} level [41]. Therefore, it can be neglected in atomic cooling experiments.

Thus, according to the above analysis, we can exclude the effects of temperature, creep, optical power, and pressure changes on the long-term frequency drift. Therefore, the most likely reason for such drift is release of system stress, and the linear drift of frequency after many measurements indicates that the rate of stress release is a constant, which is consistent with the results in [42–44].

In our experiment, the undesired stress arises mainly from two sources. The first is the copper wire that is suspended in the chamber to reduce heat conduction and that inevitably generates stress. The second source is the epoxy AB glue that we use to stick the PZT and cavity together: stress may be produced during glue solidification. To address these sources of stress in future experiments, we may be able to use softer wire and to change the method of adhesion, such as by using anodic bonding [45].

Although the short-term drift of the PZT has been greatly eliminated through using two PZT layers, there is still a long-term drift due to release of stress. The velocity of this long-term frequency drift has been measured, and therefore the process of stress release can be compensated by compensating the voltage of the PZT. The drift rate only needs to be calibrated every few weeks by atomic or ionic fluorescence. The final result is shown in Fig. 7. Compared with the most accurate commercial wavemeters (WS8-2, HighFinesse, absolute frequency accuracies is 10 MHz in UV wavelengths and recommended calibration period ≤ 2 minutes), our method has great advantages in terms of frequency stabilization accuracy and calibration time period.

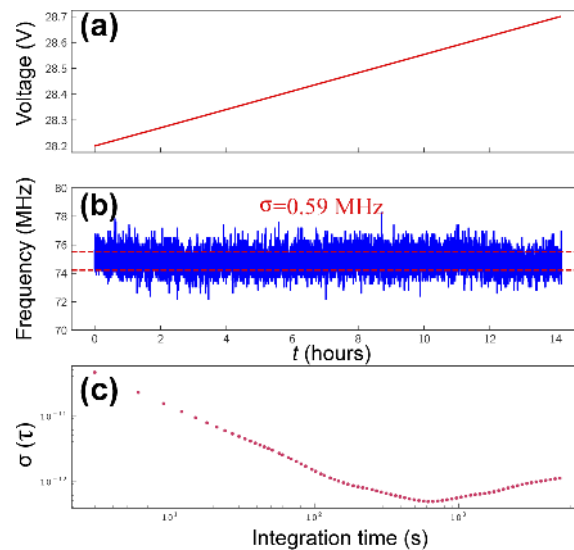


Fig. 7. Beat frequency results after compensating the PZT voltage. (a) Voltage of the PZT in the FP cavity. The compensation rate is 0.36 V/h. (b) Beat frequency with reference laser. The long-term drift of frequency is eliminated by compensating the cavity voltage. (c) Measured Allan deviation as a function of averaging time.

Figure 7(a) shows the variation of PZT voltage. In this experiment, linear compensation is adopted for convenience, with a compensation rate of 0.36 V/h. Figure 7(b) shows the result for the beat frequency. This frequency is 74.9 MHz and the recording time is 14 h. The short-term frequency fluctuation is 0.59 MHz, and the long-term drift of the center frequency is eliminated by compensating the voltage of the PZT, which is sufficient for cooling $^{171}\text{Yb}^+$. Figure 7(c) shows the Allan deviation as a function of averaging time, and the frequency stability of the laser has reached the minimum 4.8×10^{-12} for an integration time of 615 s.

If the high-speed Proportional-Integral-Derivative (PID) module is used, such as a FALC 110 (TOPTICA), the feedback bandwidth can be increased by at least one order of magnitude, and if the finesse can reach about 600, the short-term frequency fluctuation will be less than 10 kHz. In general, if the aim is only to cool ions or atoms, then current results can fully meet experimental needs, but if stricter frequency stability is needed, then these suggested improvements are worth considering.

4. Conclusion

In summary, we have demonstrated a simple and stable laser frequency stabilization method with large tuning range that uses a special PZT structure. This method can stabilize the daily drift of the UV laser center frequency at the MHz level without the need for an external reference or a vacuum environment. And its frequency stability performance has been better than that of the most accurate commercial wavelength meter. Moreover, this long-term drift is eliminated by compensating the cavity voltage with an open loop. If it is combined with multiwavelength stabilization technology [3,12,46], the laser frequency stabilization system will be greatly simplified. Compared with previous frequency stabilization methods, our method has both greatly improved the long-term frequency stability and widened the tuning range. Therefore, it has great prospects for application in experiments with cold atoms and trapped ions.

Funding. National Key Research and Development Program of China (2016YFA0302700, 2017YFA0304100); National Natural Science Foundation of China (11734015, 11774335); Key Research Program of Frontier Science, Chinese Academy of Sciences (QYZDY-SSW-SLH003); Chinese Academy of Sciences (ZDRW-XH-2019-1); Fundamental Research Funds for the Central Universities (WK2470000026, WK2470000027, WK2470000028); the Anhui Initiative in Quantum Information Technologies (AHY020100, AHY070000); the National Program for Support of Topnotch Young Professionals (BB2470000005).

Disclosures. The authors declare no conflicts of interest.

Data availability. 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.

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