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ABSTRACT

We present a simple motorized rotation mount for a half-wave plate that can be used to rapidly change the polarization of light. We use the device to switch a high power laser beam between different optical dipole traps in an ultracold atom experiment. The device uses a stepper motor with a hollow shaft, which allows a beam to propagate along the axis of the motor shaft, minimizing inertia and mechanical complexity. A simple machined adapter is used to mount the wave plate. We characterize the performance of the device, focusing on its capability to switch a beam between the output ports of a polarizing beam splitter cube. We demonstrate a switching time of 15.9(3) ms, limited by the torque of the motor. The mount has a reaction time of 0.52(3) ms and a rotational resolution of 0.45(4)°. The rotation is highly reproducible, with the stepper motor not missing a step in 2000 repeated tests over 11 h.

I. INTRODUCTION

Dynamic control of the polarization of light is a common requirement in many optical experiments. The rotation of a polarizer or a wave plate using a purpose-built rotation mount is a common method of polarization control. Desirable characteristics of a motorized rotation mount include high resolution, short rotation times, high repeatability, smooth rotation profiles, and simple control. Common designs use servo motors and stepper motors,[1–4] where the rotation of the shaft is transmitted to a receptacle for the optic using a series of gears[3] or a belt.[4] Commercial models often prioritize resolution over speed and typically take over 100 ms to rotate 45°.

Polarization control is frequently used to switch the power of a laser beam between different optical paths.[5–7] In experiments involving ultracold matter, where high-power laser beams are commonly used to trap atoms,[8] it is often desirable to be able to divert the output of a single high-power laser between multiple traps during the experimental sequence. For a linearly polarized beam of power P_0 incident on an ideal polarizer, the power of the transmitted beam P_T is given by Malus's law: $P_T = P_0 \cos^2(\theta)$. Here, θ is the angle between the polarization of the incident beam and the axis of the polarizer. It follows that a 45° rotation of a half-wave plate (HWP) can be used to completely switch a beam between the output ports of a polarizing beam splitter (PBS) cube.

This work is motivated by the need to switch a 30 W laser beam between two optical dipole traps in less than 50 ms while avoiding losses associated with the limited diffraction efficiency of acousto-optic modulators. Our solution is designed around a stepper motor with a hollow shaft, similar to the device used in Ref. 9. Such devices are designed to allow for the use of custom motor shafts or the passage of wiring through the motor. In our case, we transmit a laser beam through the hollow shaft of the motor and attach a HWP directly to the end of the shaft. This design has the advantage that the axis of rotation of the motor passes through the center of the HWP, reducing the moment of inertia and enabling fast switching times. Below, we report the details of the design and performance of our rotation mount. We show that it is able to reproducibly switch the light between the two output ports of a PBS with switching times as low as 15.9(3) ms.

II. THE ROTATION MOUNT

The rotation mount uses a stepper motor with a hollow shaft, with adapters to attach the wave plate to the motor shaft and the motor to an optical breadboard [Fig. 1(a)]. We use the SCA4218M1804-L NEMA-17 hollow stepper motor.[10] The NEMA-17 model was selected for its balance of torque and mechanical size. The motor shaft has an inner diameter of 8 mm. The HWP has a diameter of 12.7 mm and is attached to the motor shaft using a compact adapter, minimizing unnecessary inertia and hence maximizing the rotary acceleration of the mount. In a stepper motor, motion is discretized into well-defined steps, which allows for reliable open-loop control. The full step size of this motor is 1.8°. Stepper motors can also be run in a micro-stepping configuration, which reduces the step size, allowing for smoother rotation profiles and higher resolution.[11] We operate under half-stepping and quarter-stepping, which give step sizes of 0.9° and 0.45°, respectively. Further divisions are possible and would allow even more precise motion, but they are not required for our application.

The electronics required to operate the motor are readily available due to the popularity of stepper motors in hobbyist 3D printing. An Arduino UNO microcontroller is used to interface with a motor driver chip, which provides the current waveform for the motor. We use the driver chip TMC2208, as we found it significantly reduces mechanical vibrations. A detailed guide to setting up the rotation mount, including a bill of materials for the electronics, can be found in the supplementary material. Mechanical designs for the adapter parts and microcontroller codes are available.[12]

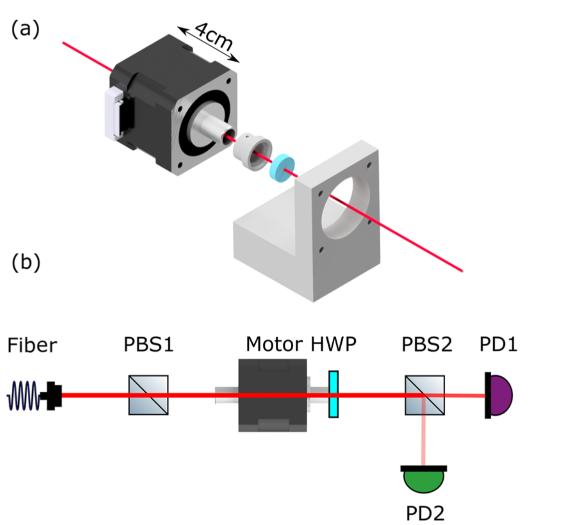

FIG. 1. (a) The hollow stepper motor along with the adapter for a half-inch diameter wave plate and an L-shaped mounting bracket. The motor shaft is hollow, with an inner diameter of 8 mm, which allows a laser beam to pass through it as shown. (b) The setup used to test the rotation mount. The first polarizing beam splitter (PBS) cube sets a well-defined polarization into the rotation mount. By measuring the power out of the two ports of a second PBS with photodiodes (PD), we can extract the angle of the half-wave plate (HWP), independent of the power fluctuations of the beam.

A. The test setup and general operation

For testing the rotation mount, we use a setup where the mount diverts an incident beam between the two output ports of a PBS and onto two photodiodes [Fig. 1(b)]. The orientation of the HWP sets the polarization of the light into PBS2 and, hence, the fraction of the beam that reaches each photodiode. To ensure a well-defined linear polarization into the rotation mount, we use another polarizer, PBS1.

We operate the rotation mount in two different configurations—the testing configuration and the switching configuration. In the testing configuration [the gray area of Fig. 2(a)], the mount rotates between half maxima of the power to maximize angular sensitivity at the start and end of a 45° rotation. In our ultracold matter experiments, we use the switching configuration [the pink area of Fig. 2(a)], where the beam is switched between two different paths over the course of a rotation. We define the switching time as the time taken for a 45° rotation (a switch). We can use the relative power of the transmitted beam to calculate the angular orientation of the HWP using Malus's law. The performance of the rotation mount is assessed using the testing configuration.

We use a position ramp characterized by a constant acceleration (as recommended in Ref. 11), where we accelerate the motor to a maximum velocity and then decelerate to rest over the course of a switch. We use quarter and half micro-stepping to improve the resolution and reduce vibrations. The required waveform is generated by the Arduino AccelStepper library.[13] With a linear velocity ramp, the time between the mth and $(m+1)$th pulses into the stepper motor is given by[14]

$$t_m = 2\left(\sqrt{\frac{m+1}{a}} - \sqrt{\frac{m}{a}}\right), \tag{1}$$

where a is the acceleration of the motor in steps s^{-2}. Given that the first pulse occurs at $t = 0$, we consider the time for the motor to turn as the time taken for d pulses, where d is the number of steps in the rotation (rotation angle/step size).

B. Control of rotation dynamics

The profile of a single switch in the testing configuration is shown in the inset of Fig. 2(b). The switch is triggered by a pulse to the microcontroller. The time between the trigger pulse and the motor starting to move is the reaction time of the device. The rotation mount then rotates the HWP through 45°, changing the power between the two beam paths.

The reaction time of the motor is measured at 0.52(3) ms. We measure this as the time taken after the trigger pulse for the power transmitted through the PBS to change by 0.5% of the initial power (the smallest value we can reliably resolve). At the half maxima, this corresponds to a rotation of 0.07°.

Figure 2(b) shows the switching time plotted as a function of acceleration alongside the expected behavior from Eq. (1). The switching time is measured as the time between the trigger pulse and the first inflection point after the switch [black lines in Fig. 2(b) inset], where the motor is no longer moving in the intended direction.

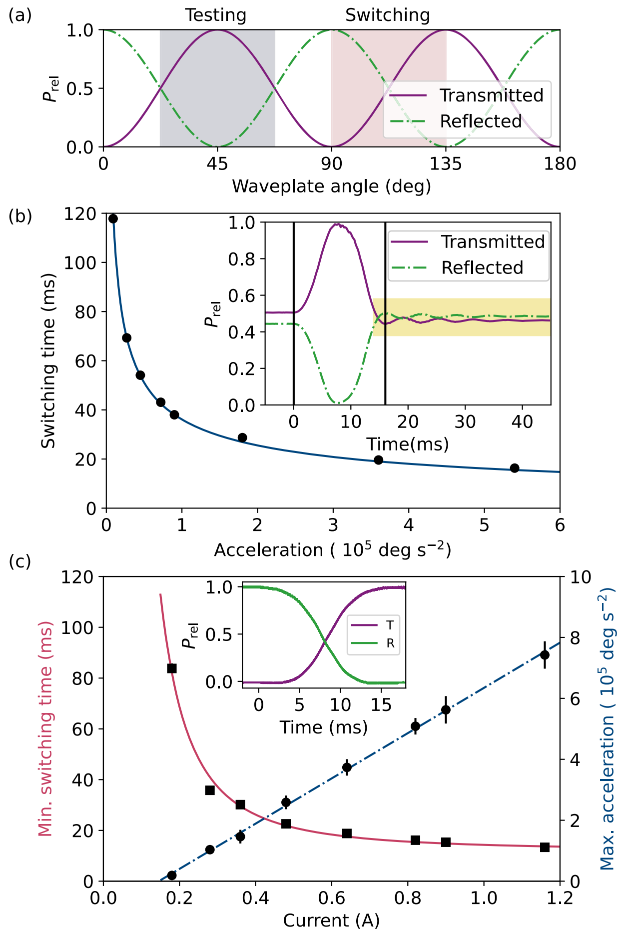

FIG. 2. (a) Predicted beam power as a function of wave plate angle. P_{rel} refers to the power measured at a PD normalized to the full beam power. The gray and pink areas correspond to the testing and switching configurations, respectively. Typical signals associated with each configuration are shown in the insets of (b) and (c). (b) Switching time vs acceleration using half-stepping. The blue line is the predicted behavior given in Eq. (1), and the black points are the measured times. The black lines in the inset show the start and end of the switch. Each point is the average of five measurements and was taken with the motor current limit set to 1.0 A. The typical uncertainty of the switching time is less than 0.4 ms. (c) Minimum switching time and maximum acceleration as functions of current. The maximum acceleration is directly proportional to the current, implying a torque-limited behavior. The inset is the signal at a current of 0.96 A, demonstrating switching in under 20 ms.

Figure 2(c) shows that the switching time is limited by the current into the motor and, hence, the torque output of the motor (see the supplementary material for further details). At a current of 1.0 A into the motor, the maximum acceleration of the motor with the wave plate attached is $6.0(2) \times 10^5$ deg s^{-2}. The quickest measured switching time was 15.9(3) ms.

We observe a damped oscillation of the motor with a maximum amplitude of between 0.4° and 0.7° at the end of every switch; a known feature of stepper motors.[11] When operating in the intended switching configuration, the impact of this oscillation is greatly reduced owing to the $\cos^2(\theta)$ dependence of Malus's law and we observe less than 0.1% variation in the transmitted signal. We have found that the choice of the driver can dictate the amplitude of these oscillations (see the supplementary material).

C. Reliability and repeatability

We tested the reliability and repeatability of the device by leaving it to run for 2000 switches over a period of 11 h in a half-stepping configuration at a switching time of 39 ms. We set the motor to move forward 45° every 20 s to check for any accumulation of errors. With ideal operation, the motor would return to the same position after every eighth switch. However, a skipped micro-step during a switch would result in an offset in the position of the motor by 0.9° (a half-step) for each subsequent switch.

We attach a mask to the rotation mount for this measurement. The mask is oriented such that one of its opaque regions with a sharp edge obscures half the beam at the start of a switch. We measure the power of the transmitted beam on a photodiode at the start of every full rotation of the mask, as well as the full power, midway through the switch when the entire beam is incident on the photodiode. We then calculate the fractional transmission when the beam is cut in half, effectively normalizing for drifts in laser power over the course of the measurement. A skipped micro-step during a switch would appear as a 3% change in fractional transmission at the start of a switch. The standard deviation of the fractional transmission over the full period of measurement is 0.12%, with the single largest deviation being 0.37%. This 0.12% standard deviation in fractional transmission corresponds to 0.04°, which we take to correspond to the measurement uncertainty in the resolution of the stepper motor. We conclude that the motor did not miss a step in the 11 h of testing and is, therefore, reliable enough for open loop operations.

III. CONCLUSION

In conclusion, we have presented a motorized rotation mount that can be used to rapidly switch the polarization and, hence, the path of a high power laser beam in under 20 ms. We have implemented the rotation mount in our ultracold atom experiment, where a 45° rotation is used to repurpose power from one laser to different beam paths. We are, hence, able to use the full power from one laser for different optical dipole traps at different times in our experimental sequence. Smaller rotations of the HWP can be used to control the power to each path and, hence, the depth of the optical dipole traps. The ease of construction and operation of the device facilitates wide adoption in similar experiments where the switching of beam paths is a common problem.

SUPPLEMENTARY MATERIAL

See the supplementary material for a guide to setting up the rotation mount and for a discussion of the torque limitations and overshooting oscillations.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Adarsh P. Raghuram: Conceptualization (supporting); Formal analysis (lead); Investigation (lead); Methodology (equal); Visualization (lead); Writing – original draft (lead); Writing – review & editing (equal). **Jonathan M. Mortlock**: Conceptualization (lead); Formal analysis (supporting); Investigation (supporting); Methodology (equal); Writing – review & editing (equal). **Sarah L. Bromley**: Supervision (supporting); Writing – review & editing (equal). **Simon L. Cornish**: Funding acquisition (lead); Supervision (lead); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are openly available in the Durham University open data repository at http://doi.org/10.15128/r1n870zq866.

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