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Note: Fast compact laser shutter using a direct current motor and three-dimensional printing

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We present a mechanical laser shutter design that utilizes a direct current electric motor to rotate a blade which blocks and unblocks a light beam. The blade and the main body of the shutter are modeled with computer aided design (CAD) and are produced by 3D printing. Rubber flaps are used to limit the blade's range of motion, reducing vibrations and preventing undesirable blade oscillations. At its nominal operating voltage, the shutter achieves a switching speed of (1.22 ± 0.02) m/s with 1 ms activation delay and 10 μs jitter in its timing performance. The shutter design is simple, easy to replicate, and highly reliable, showing no failure or degradation in performance over more than 10^8 cycles. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4937614]

Fast and robust optical shutters are essential to many laser-based experiments, as well as technological applications. These experiments, spanning a wide range of research areas in science and engineering, require the shutter to have the following performance characteristics: short switching time, small activation delay, high timing precision or low jitter, low vibration and heat dissipation, an aperture size capable of accommodating the relevant beam sizes, high extinction ratio, laser power handling sufficient for the blocked beam, and a long operation lifetime.

To be useful for precise laser experiments, shutters require excellent timing performance, with short activation delays, fast switching times, and low timing jitters. A short activation delay allows for the generation of short light pulses, and a fast switching time allows for generating pulses with well-defined edges. A small timing jitter allows precise timing control and synchronization with other parts of the experimental apparatus. These three qualities are necessary for the shutter to quickly and accurately realize a desired laser intensity profile over time.

A shutter can be operated based on a large variety of mechanisms. Shutters based on electro-optical and acousto-optical modulators are very fast and hence have excellent timing performance, but require careful alignment. Most importantly, these types of shutters are unable to provide full extinction and transmission of the incident light, which can only be achieved by mechanical shutters. Many commercial laser safety interlock and diaphragm shutters exist,[1,2] but they are typically not designed for precise timing applications in optics experiments; these shutters do not possess the desired timing performance and produce high noise and vibrations during operation. Commercial shutters with the requisite high performance[3,4] have costs that are impractical for typical laboratories, which can require tens of shutters.

Lacking satisfactory commercial options, various laboratories have developed custom-made mechanical shutter systems.[5–11] However, we find that these designs have drawbacks that limit their usability. Systems that utilize piezo-actuators provide fast switching times and low timing jitter,[5] but have insufficient extinction ratios and small sweep ranges. A design based on the modification of voice-coil motors in computer hard disk drives achieves both high speeds and a large aperture diameter,[8] but is too bulky in size for flexible placement in most optical setups. Another design, based on the thermal expansion of NiCr wire, achieves activation delay of less than 300 μs,[11] but cannot operate at repetition rates with switching intervals shorter than 5 s due to the long relaxation time required for the thermal recovery of the wire.

Most importantly, the aforementioned shutter designs capable of high speed and precision all require complicated and delicate assembly. This leads to three major disadvantages that severely restrict the large-scale application of these shutter designs. The difficult assembly process makes it hard to construct and maintain the shutters in the quantities typically required by a laboratory. Higher complexity decreases the reliability of the shutter as the overall shutter system contains more elements vulnerable to mechanical or electrical malfunctioning; this is especially important for applications that

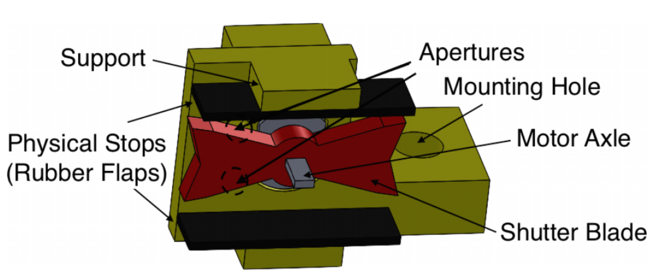

FIG. 1. CAD rendering of the shutter design. There is an upper aperture and a lower aperture, symmetric about the height of the motor axle, through which the laser beam can travel. The motor axle rotates the shutter blade to alternately block and unblock each aperture.

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require long-term operation. Finally, the high sensitivity of each shutter to fine variations in its construction process causes performance inconsistency among separate shutter units.

In this article, we present a compact and high-performing shutter system that is easy to construct and replicate consistently. The main components of the shutter are the 3D printed plastic mount and shutter blade, a direct current (DC) electric motor, and an electrical driver circuit. Detailed procedures for assembly are described in the supplementary material.[12] Assembly of the shutter and driver takes under an hour when provided the required materials, which consist of easily obtainable electrical components and 3D printed ABS plastic structures that can be produced in any desired quantity in one operation. Testing of the design shows both high speed and high reliability; the shutter has operated with sub-millisecond switching time for over 10^8 cycles without degradation.

The shutter design is presented in Fig. 1. The DC motor rotates the shutter blade which blocks and unblocks the laser beam. The motor axle and the hole in the blade through which it is inserted are flattened to prevent slipping between during operation. Two neoprene rubber flaps, attached to the support by adhesive, act as physical stops to halt the motion of the blade and to dampen vibrations from the blade that would otherwise cause it to bounce back and lead to undesirable transient blocking or unblocking of the beam. Laser beams can travel through the upper or lower aperture, both of 2.5 mm width, which are alternately blocked and unblocked during operation. The shutter can be secured to an optical post through the mounting hole, as shown in Fig. 2, and is compact enough to be inserted into any optical setup.

The electrical circuit of a single shutter driver, presented in Fig. 2, primarily consists of a H bridge and a pulse-generating RC circuit similar to another reported design.[9] The circuit allows for bipolar driving of the motor with a unipolar electrical supply. The timing sequence of the opening and closing of the shutter is controlled by the transistor-transistor logic (TTL) input signal.

This shutter design demonstrates excellent timing performance through its short activation delay, fast switching time, and low timing jitter. A fast avalanche photodiode (APD) was used to measure the transmission of a laser beam through the aperture during repeated blade transitions, giving the activation delay and the switching time of the shutter. Opening and closing delay times are between 1 and 2 ms, depending on the alignment of the laser beam through the shutter aperture. The speed of the shutter blade, measured by clipping an expanded laser beam with a metal sheet and determining the delay time taken by the shutter to provide complete extinction of the incident laser beam, was found to be (1.22 ± 0.02) m/s at the nominal operating voltage of 9 V. The activation delay and switching time decrease with the operating voltage, as shown in Fig. 3. The typical jitter ranges in activation delay and switching time were measured to be about 20 μs and 10 μs, respectively, also decreasing with increased operating voltage. The jitter of the shutter's timing response over 1000 measurements in a sample period of 14 h is shown in Fig. 4, illustrating the high mechanical stability provided by rubber flaps in arresting the motion of the shutter blade.

The shutter shows high consistency in the timing performance between each unit. The performance variation between different shutter units is smaller than the performance variation caused by removing the shutter from the setup and placing it back in the same position.

The shutter operates under low power, thereby extending its functional lifetime. Its mechanical motion is bistable, requiring only 2-3 mA of current to keep the blade in its raised or lowered position, in contrast to the 100 mA required by unstable shutters.[6,8] Its operating voltage range is 4–15 V. Below 4 V, the motor cannot overcome static friction to actuate the blade motion, while above 15 V, excessive driving force causes the blade to bounce back from the rubber flap and produce

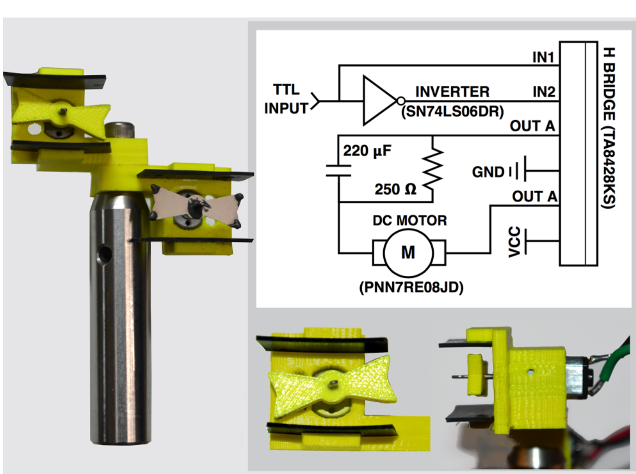

FIG. 2. Shutter units stacked on an optical post (left), side view of shutter with plastic blade (bottom right), and the circuit schematic for a single shutter driving circuit, with part numbers indicated (top right).

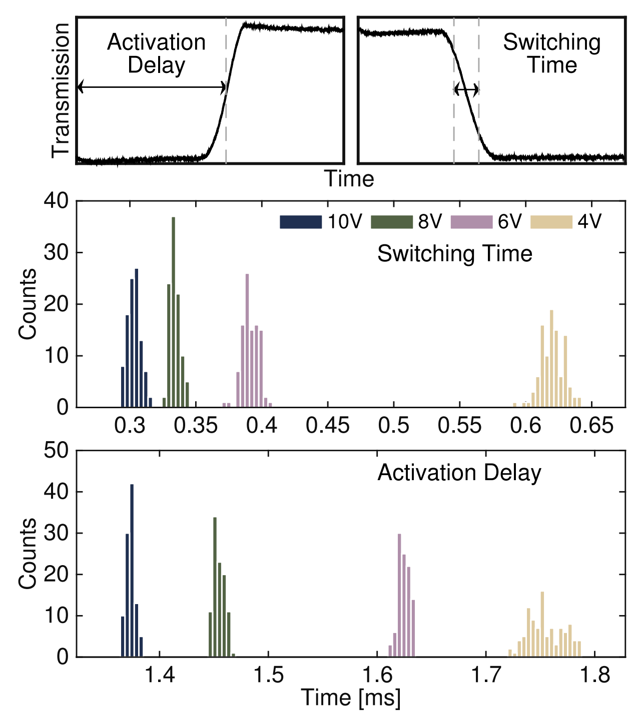

FIG. 3. Distribution of 100 measurements of activation delay, the time interval between the application of the TTL signal and 50% transmission, and switching time, the time interval between 80% transmission and 20% transmission, at different operating voltages V_{CC}.

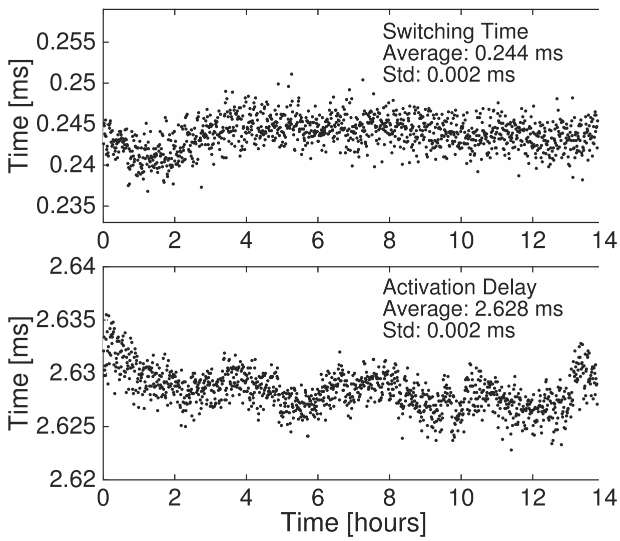

FIG. 4. Jitter range of delay times (top) and switching times (bottom) over 14 h at operating voltage $V_{CC} = 9$ V.

transient blockage or opening of the aperture. Operation at 9 V only dissipates 13 mJ of energy in the shutter motor during each transition.

The shutter has maximum short-term and long-term repetition rates of 110 Hz and 20 Hz, respectively. These limitations are due to the ABS plastic softening from high heat dissipation by the motor and could be solved by adding a heat sink to the mounting structure or by fabrication of the shutter components from more heat-resistant materials. The plastic blade has a laser power-handling of 50 mW for a beam size of 1 mm, but can be replaced by metal, as shown in Fig. 2, the surface of which could be painted black to absorb and dissipate energy from the laser. We estimate that this would increase the power-handling limit to above 1 W.

The shutters produce minimal noise and vibrations. At an operating voltage of 4 V, operation is not detectable by ear. Noise and vibration could be further reduced by adding electronic braking to the driver circuit.

Applications of this shutter design can be extended by replacing the opaque blade with an optical component. In this way, one can remotely place components such as a polarizing element or a wave plate in and out of the path of a laser beam. The low timing jitter is equivalent to a high repeatability of the blade position during each shutter cycle, suggesting that even alignment-sensitive elements such as lenses or prisms could replace the blade for control over the aligning or focusing of the laser beam.

In conclusion, we have designed and implemented a simple, compact, robust, low-noise, high-performance laser shutter, based on a small commercial DC motor, 3D printed shutter body and blade, and rubber motion stops. The shutter has a lifetime and timing performance comparable to commercial shutters with both very low cost and construction time. Most importantly, this shutter is easy to reproduce in large numbers with high consistency, as the mechanical structure is fixed by the computer aided design (CAD) file used for 3D printing, requires no extra tinkering during assembly, and is highly reliable due to the elimination of variations in assembly and the simplicity of the mechanism. We expect this design to be highly useful in laser experiments across many disciplines, where it could fill a niche where commercial options are currently limited.

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