Note: Fast, small, and low vibration mechanical laser shutters

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We present three novel mechanical laser shutter designs based, respectively, on a stepper motor, a relay, and a piezoelectric actuator. Each shutter type is ideally suited to a specific shuttering application. The stepper motor is well suited for applications requiring low vibrations, the relay is compact and capable of rapid bursts, and the piezoelectric is 2 orders of magnitude faster than other available mechanical shutters. © *2011 American Institute of Physics*. [doi:10.1063/1.3574224]

The optical shutter is a basic element of laser-based physics experiments. Commercially available shutters[1] are expensive and generally suffer from some combination of high vibration, low pulse rate, or large size; so, experimenters frequently construct their own shutters.[2–4] We have found these published alternatives to be of limited application to our own needs. The speaker-based shutter[2] suffers from delicate construction and limited reliability. The hard disk shutter[3] requires significant space, has a limited repetition rate, and care must be taken to reduce vibrations. The piezoelectric shutter[4] has a low extinction ratio. We present three novel designs that overcome the limitations of current shutter designs and are simple to implement. The first shutter is based on a stepper motor with reduced vibrations. The second uses a compact relay with high burst rate. The third is based on an extended piezoelectric actuator and has very low jitter and a very fast repetition rate with a high extinction ratio. The choice of shutter depends on the application, since each shutter has a specific set of characteristics that differentiates it from the others. Table I compares the performance of lab-implemented shutters, with the last three corresponding to the current work. We have found these relatively low-cost shutters to be very convenient for our atomic physics experiments.

The first shutter uses a stepper motor from an inkjet printer with a step of 7.5°. A solid rod attached to the motor has a shuttering flag displaced by 4 cm from the rotating axis [Fig. 1(a)]. The circuit of Fig. 2(a) changes the shutter position by a single step. It can be triggered with a toggle switch (S1) or an external transistor–transistor logic input. We achieve fast shuttering (27 μs) by focusing the laser beam at the position of the flag with a 5 cm lens.

As opposed to commercial shutters there is no physical stop involved. Instead, the flag position is controlled by the magnetic field coils in the motor. The vibrations introduced were not visible in our laser locking signals, even when placing the shutter right next to the laser. With the stepper motor shutter it is possible to have more than two positions by sending additional control pulses to inputs 10 and 15 of the L293 chip [Fig. 2(a)]. We use the additional positions to partially block the laser beam and use it as a variable attenuator (Fig. 3).

A compact and inexpensive shutter can be constructed using an automotive relay. We glue a brass flag to the relay arm (Tyco Electronics T90N1D12-12) to shutter a laser beam when a current is applied [Fig. 1(b)]. The shutter is based on the unpublished design of Meyrath,[6] but with some improvements: (1) the flag consists of a hollow brass tube (3 cm) and stiff brass sheet for added strength against flexing and (2) the driver circuit has been upgraded for faster charging of the discharge capacitor. The automotive relay has a high relia-

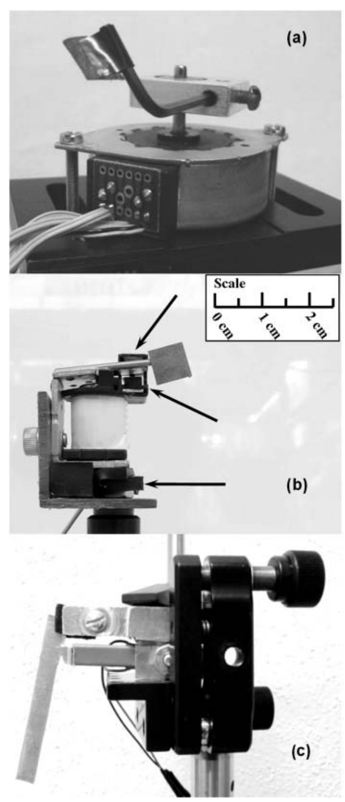

FIG. 1. Shutters: (a) stepper motor, (b) relay, and (c) piezoelectric actuator. The arrows in subfigure (b) indicate where sorbothane has been installed to provide vibration damping.

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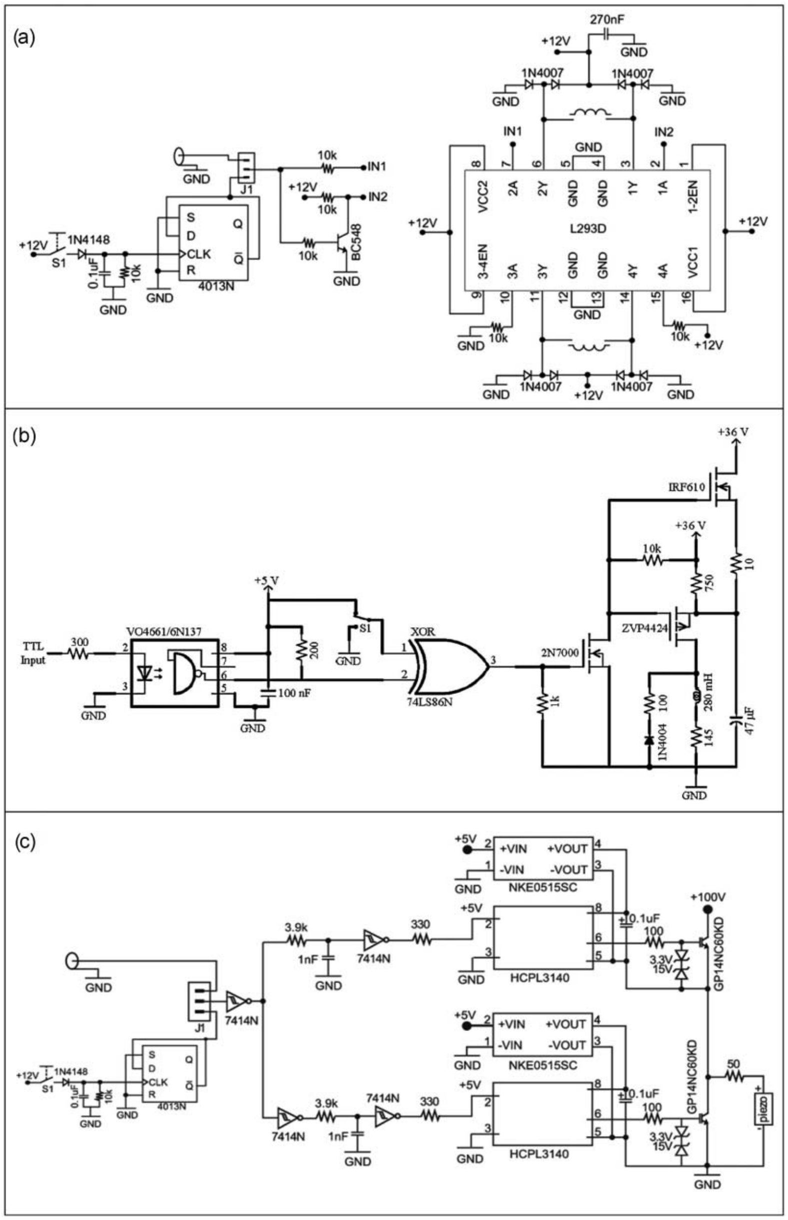

FIG. 2. Circuits used to drive: (a) stepper motor, (b) relay, and (c) piezoelectric actuator. Heat sink required for: (a) L293D, (b) 750 Ω, and (c) IGBT.

bility and a compact footprint: it has a lifetime of 10^7 cycles over an operational temperature range of -40 to 85 °C and is smaller than 3 cm on the side. The shutter is easily attached to standard optomechanics, and its small size makes it easy to insert into existing optical setups and to be used with very low beam heights.

Figure 2(b) shows the circuit used to drive the relay. A XOR gate allows for both manual and externally triggered shutter operation simultaneously. This gate closes the relay via a MOSFET-based circuit that sends a brief (10 ms) 36 V pulse to the relay, powered by the discharge of the 47 μF capacitor. The P-channel MOSFET controls the discharge, while an N-channel MOSFET provides rapid recharging of the capacitor.

These shutters generally achieve a maximum repetition rate of 65 Hz, though some can operate at up to 90 Hz with burst rates of a few pulses at up to 125 Hz. By placing the shutter flag at a laser focus, the shutters can typically pulse a laser on or off for as little as 3 and 5 ms, respectively.

We isolate our lasers from relay-produced vibrations by mounting the shutter assembly onto an aluminum plat-

TABLE I. Performance of different shutter designs.

Mechanism	Speed (m/s)	Sweep (mm)	Jitter (μs)	Rate (Hz)	On/Off
Loudspeaker (Ref. 2)	1.7	5.3	10		∞
Hard disk (Ref. 3)	10	32	6.5	30	∞
Piezo (Ref. 4)	1	0.01		10^4	300
Thermal expt. (Ref. 5)	16	>3			
Stepper motor	0.93	5	100	40	∞
Relay	0.9	3	100	65	∞
Extended piezo	0.73	0.042	0.1	10^3	>1600

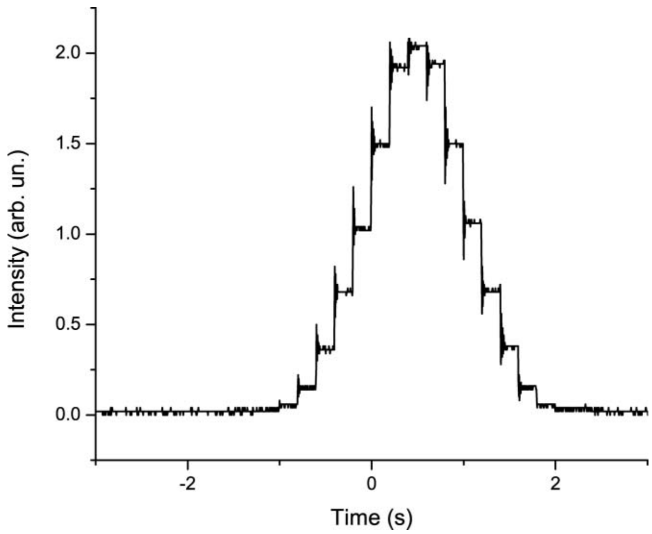

FIG. 3. Approximate Gaussian pulse generated with the stepper motor shutter by varying the duration and direction of each step.

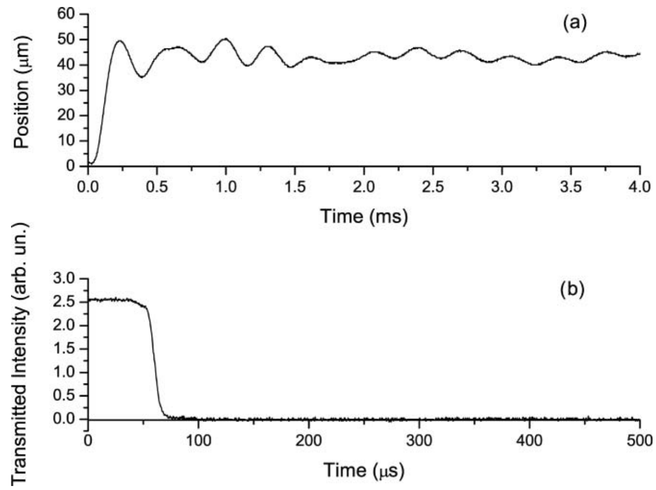

FIG. 4. (a) Piezoelectric actuator shutter displacement as a function of time. (b) Transmitted intensity when the shutter is at the focal point of the lens.

form that is secured to the optics table through 1.5 cm thick vibration isolation foam (Pinta-Acoustics Willsuct ceiling tile material) and thin pieces of sorbothane. These isolating materials strongly suppress shutter-produced excursions of our laser lock error signals to a barely perceivable level, even when averaged over many shutter cycles.

Acousto-optic and electro-optic modulators are used for experiments requiring submicrosecond timing precision. An alternative is to use a piezoelectric-based shutter where the expansion of a piezo element is used to block a laser beam. The laser beam needs to be tightly focused due to the small expansion (10 μm) of piezoelectric actuators.[4] Complete extinction of the laser is only possible if the displacement of the piezo is much larger than the beam waist.

We use a 11 mm focal length lens to produce a $(1/e)$ waist of 13 μm at the focal position (Rayleigh length of 145 μm). We add a lever arm to amplify the piezoelectric actuator (Thorlabs AE0505D18) displacement (10 μm with 100 V) to 42 μm [Fig. 1(c)]. Figure 4(a) shows a measurement of the displacement of the piezo as a function of time. We minimize the vibrations at the final position of the shutter by increasing the stiffness of the lever arm both by clamping it harder on the fixed side and by using a thick aluminum flag along the direction of motion. We achieve an extinction ratio better than 1600 : 1 once the vibrations damp out and better than 400 : 1 for the biggest bounce [Figs. 4(a) and 4(b)]. The beam comes directly out of a laser diode with no spatial filtering. We position the shutter using a prism mount (Thorlabs KM100P) which avoids the need for micrometer stages.

We drive the shutter using two insulated gate bipolar transistor (IGBT) switches to quickly charge and discharge the piezo [Fig. 2(c)]. The control signal to one of them is the negative of the other to prevent a short circuit of the supply. The 50 Ω resistance value was optimized to make the motion of the piezo fast but smooth, in order to reduce vibrations.

The delay between the control pulse and the actual shuttering of the beam is now 12 μs and the shot-to-shot jitter is 0.1 μs which is 2 orders of magnitude smaller than other shutter types. Very high repetition rates are possible since the resonant frequency of the piezo is 69 kHz (without load). In practice the repetition rate is limited to about 1 kHz by the heating of the dc/dc converter [Fig. 2(c)]. Light pulses shorter than 1 ms can still be produced as long as the repetition rate is low. The amount of mass moved by the piezo is small, and we do not observe any shutter vibration effects on our laser locking signals.

In conclusion, we have implemented and tested three novel types of shutters that are economical, simple to construct, and competitive with existing shutters. The stepper motor shutter introduces low vibrations and can be configured as a variable attenuator. The relay shutter is quite compact and reliable and can be operated in burst mode for multiple rapid exposures. Both shutters can be used to quickly insert transmissive optical elements such as filters, waveplates, and attenuators. The piezo shutter is very fast and has a shot-to-shot jitter 2 orders of magnitude better than other mechanical shutters. We find these designs to provide excellent shuttering in many laser physics applications, including laser cooling and trapping experiments.

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[1] Thorlabs SH05, Newport 71445, SRS 475, Uniblitz LS2, Edmund NT59-596, EOPC CH-40 or EOPC SH-10 among others.
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[6] See http://george.ph.utexas.edu/~meyrath/informal/shutter.pdf for T. Meyrath, "Inexpensive mechanical shutter and driver for optics experiments."