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REVIEW OF SCIENTIFIC INSTRUMENTS **89**, 126102 (2018)

Note: A simple laser shutter with protective shielding for beam powers up to 1 W

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We present the design of an inexpensive and reliable mechanical laser shutter and its electronic driver. A camera diaphragm shutter unit with several sets of blades is utilized to provide fast blocking of laser light and protective shielding of the shutter mechanism up to a laser beam power of 1 W. The driver unit is based on an Arduino microcontroller with a motor-shield. Our objective was to strongly reduce construction effort and expenditure by limiting ourselves to a small number of modular parts, which are readily available. We measured opening and closing durations of less than 800 μs, and a timing jitter of less than 25 μs for the fastest set of blades. No degradation of the shutter performance was observed over $5{\cdot}10^4$ cycles.
https://doi.org/10.1063/1.5053212

Mechanical optical shutter units have become indispensable in modern optics laboratories to provide a time-dependent extinction of laser light. Depending on the application, a multitude of desirable properties can be identified, such as low extinction ratios, fast switching times, low time jitter, high reliability, high repetition rates, small sizes, or long operation lifetimes.

Commercial products are currently available that fulfil most of those design requirements at high costs,[1] but laboratories often need dozens of shutter units and commercial solutions can quickly become unaffordable. As a result, many experimental groups have developed their own shutter designs with varying design goals and technical approaches,[2] e.g., based on loudspeakers,[3] computer hard drives,[4] or piezoelectric devices.[5,6]

In this article, we present the design of a mechanical shutter and its driver unit with two design objectives. The first objective is to strongly reduce construction effort and costs while preserving fast switching times and a high reliability. We do so by limiting ourselves to a small number of modular parts which are readily available.[7,8] The shutter unit utilizes a small diaphragm shutter with multiple blades as is normally used in compact digital cameras, and the driver unit is based on an Arduino microcontroller with a motor-shield.[8] The second design objective is a protection mechanism that facilitates the blocking of laser beams up to a continuous power of 1 W. We implement the protection with a shielding blade that reflects the laser light.

Details and additional materials for the construction are available in the supplementary material. Here, we give an outline to the design of the shutter blades, the driver unit, the microcontroller software, and the enclosure of the shutter. An experimental characterisation of the switching time, the jitter, and the reliability is provided.

Figure 1 illustrates the design of the **shutter blades**. The shutter contains three sets of blades—a light pair of blades B1 that close from opposite sides of the aperture in a "scissor" motion, overlapping in the centre and blocking light; a sturdy filter blade B2 originally intended to attenuate the light in a camera; and an unused blade with a hole which only limits the aperture size B3. We utilize blades B1 for fast switching operations and blade B2 for protection and dispersive reflection of laser light. Typically, the blades of small diaphragm shutters are optimized for low weight and friction, and they start to bend or melt when absorbing laser powers of more than 50 mW. We managed to increase the beam power up to 1 W[9] by adhering a small strip of aluminum foil to filter blade B2 that dispersively reflects the laser light and dissipates heat. By our

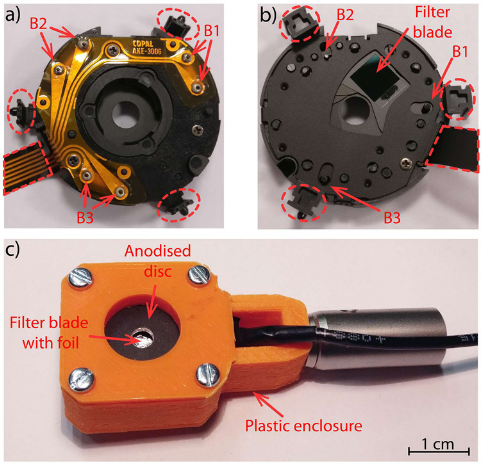

FIG. 1. Images of the (a) back and (b) front of the shutter before modifications and (c) within its 3D-printed enclosure. Red dashed lines indicate removed parts, and red arrows point toward the (a) connection terminals of the solenoids and (b) sliders of the shutter blades. The labels indicate that the connection terminals and sliders attach to scissor blades B1, filter blade B2, and unused aperture blade B3.

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design, most of the reflected light is trapped in the enclosure of the shutter.

The positions of the blades are controlled by small solenoids with independent connection terminals as indicated by red arrows in Fig. 1(a). The shutter blades are bistable without any springs or other self-restoring elements, and a short current pulse of ±200 mA for a duration of 3 ms is sufficient to flip the position. The final state of the shutter is determined by the direction of the current. For simplicity, we typically connect both blades, B1 and B2, in series by soldering thin wires to the connection terminals, but an independent control of the blades is used for the purpose of testing the shutter for this note.

The **shutter driver** consists of an Arduino microcontroller with a motor-shield (Fig. 2). The microcontroller monitors a digital (TTL) input signal that indicates the state of the shutter—a low (high) signal corresponds to a closed (open) state. The detection of a signal change triggers the short current pulse of the motor-shield with the required current direction to flip the blades. An operation of both solenoids in series requires a supply voltage of 5–6 V for the motor-shield to generate the correct current pulse. It is possible to supply the shield by the regulated 5 V output of the Arduino microcontroller, but a direct connection to the main power supply is advisable for the simultaneous control of 4 shutters units. For convenience, we added to the circuit a toggle switch to open the shutter manually, and a light emitting diode (LED) to indicate the shutter status. We intentionally limited the circuit to include only essential elements, and all components except for the microcontroller can be integrated into the front panel without the need of an additional circuit board.

Our **microcontroller software** is provided in the supplementary material. The tasks of the program are the tracking of the shutter status, the detection of a change of the TTL input signal, and the control of the motor-shield. Timer interrupts are included for the parallel control of several shutter units. The use of interrupts allows us to generate current pulses of well-defined duration without blocking the program flow. We measured a response delay between the input signal and the current pulse of 230(30) μs for a simultaneous use of 4 shutters units.

A plastic **enclosure** is used for the shutter unit to reduce the coupling of vibrations. The casing is 3D-printed using fused deposition modeling of polylactide (PLA) plastic. We sandwich the shutter between rubber "O" rings and a black anodised aluminum disc with a small hole of 4 mm diameter to further dampen vibrations. The disc reduces possible backscattering from the aluminum foil adhered to the shutter blades, and it prevents a melting of the casing material due to a misaligned laser beam. The corresponding computer-aided design (CAD)-model files of the enclosure can be found in the supplementary material.

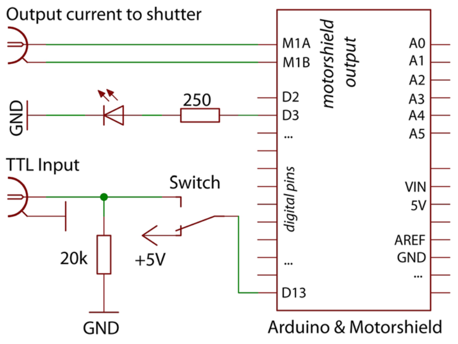

FIG. 2. Circuit diagram of the shutter controller. The design is based on an Arduino microcontroller with a motor-shield. We added a toggle switch to open the shutter manually by bypassing the TTL input signal, and an LED to indicate the status of the shutter blades. One motor-shield facilitates the simultaneous control of 4 shutter units.

The final part of this note describes an experiment to benchmark the speed, time jitter, and robustness of the shutter and driver unit. We used a photodiode[10] and an oscilloscope to measure the power of a laser beam after it propagated through the shutter. Timings for the shutter and for the acquisition oscilloscope were provided by an NI-multifunction IO device.[11] The shutter aperture is 4 mm in diameter, and the laser beam was collimated with a $1/e^2$ waist of 1.1 mm. As opposed to our normal operation, we connected each shutter blade to the shutter driver separately to study the timed opening and closing of the blades independently of one another. The intensity profiles of 500 consecutive opening and closing cycles were recorded and analyzed (Fig. 3). No degradation was detected over the course of $5 \cdot 10^4$ additional cycles.

Figure 3 shows the photodiode signal for a time t after the trigger signal to (a) open or (b) close the shutter with scissor blades B1 (blue) and filter blade B2 (red). The photodiode voltage is normalized for each data set to the signal of an open shutter. We determine an opening delay between the trigger and an increase to 5% of the full photodiode signal of 2.29(2) ms and 3.71(3) ms for blades B1 and B2. The opening durations, measured by an increase from 5% to 95% of the total signal, is 790(10) μs and 1.51(3) ms for the two sets of blades. The closing procedure is slightly faster with a closing delay of 2.73(2) ms and 2.71(3) ms and a closing duration of 573(7) μs and 1.46(2) ms for blades B1 and B2, respectively. Opening and closing delays are longer than the electronic response time, and we expect most of the delay time to be used to overcome

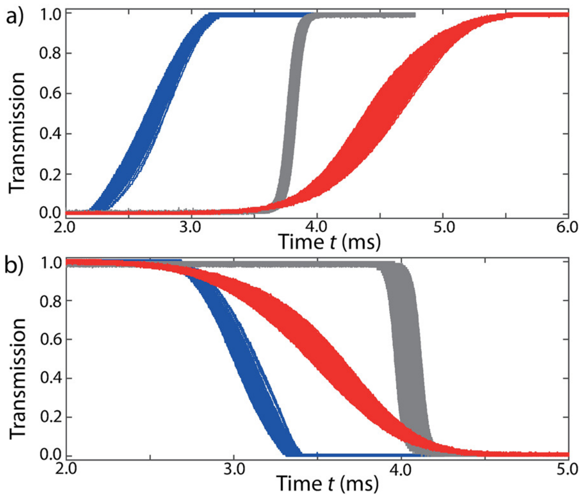

FIG. 3. Transmission signals of the two blades being (a) opened and (b) closed. The red (blue) lines show the transmission throughout the operation of filter blade B2 (scissor blades B1). The gray lines show the operation of B2 for a reduced beam waist (see text). The time scale indicates the delay time t after the change of the TTL input signal.

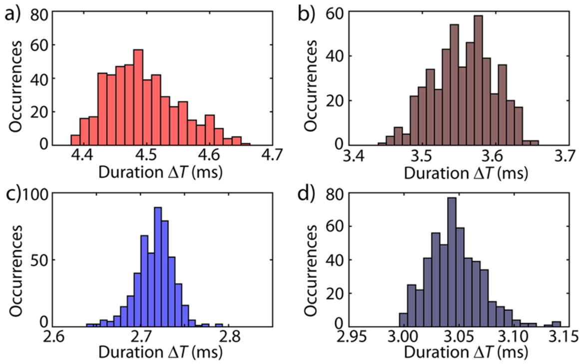

FIG. 4. Histograms of opening times for the transmission signals. (a) half-opening times and (b) half-closing times of filter blade B2. (c) half-opening times and (d) half-closing times of scissor blades B1.

friction and to separate the overlapping blades. We presume that the scissor blades are faster than the filter blade because they close in from both sides and meet in the centre of the aperture, thus traveling half the distance. Both blades have a velocity of approximately 1.2 m/s.

Another important property to characterise a shutter is the reproducibility of operation times. The histograms in Fig. 4 show the variation of the half-opening and half-closing times, i.e., the time ΔT to reach 50% of the total beam power after a change of the trigger signal. Our histograms display a low jitter time with no significant outliers. Filter blade B2 shows a positive (negative) skew of the distribution for the opening (closing) process with standard deviations of 60 μs (40 μs). The distributions of the timing of scissor blades B1 show the opposite skews with the standard deviations of 21 μs (24 μs). We speculate that this skewing is due a position dependent variation of the friction between blades, and the details of the skewing might vary from device to device. The difference in opening and closing times for the same blade might be due to a small misalignment between the center of the shutter aperture and the laser beam.

For a better comparison with other publications, we reduce the $1/e^2$-waist of the beam to 140 μm and repeat the measurements. 500 data sets for the opening and closing of blade B2 are represented by gray lines in Fig. 3. The reduced beam waist results in a reduction in the time taken for the photodiode signal to change between 5% and 95% of the total signal. For blades B1 (B2), we measure an opening duration of 137(7) μs [220(5) μs] and a closing duration of 100(4) μs [155(5) μs], which are in agreement with previous measurements and with the scaling of the beam waist.

In conclusion, we implemented and benchmarked a simple and robust shutter design based on a diaphragm shutter with multiple pairs of blades. A lightweight pair of blades is utilized for fast shutter operation while being protected by a slower and sturdier blade. The shutter can operate up to a continuous laser beam power of 1 W. For the opening and closing of fast blades B1, we measured delays of less than 3 ms, opening and closing durations of less than 800 μs (140 μs for the smaller waist) and a timing jitter of less than 25 μs. Our design goal for the shutter and driver units was to strongly reduce construction effort and costs while preserving robustness and high power operation.

Please see supplementary material for the software of the microcontroller and for the CAD-model files for the casing of the shutter.

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[1] Examples for commercial products: Vincent Associates, ES6B Laser Shutter, VED24 Shutter Driver, or Thorlabs, SHB025 Shutter.
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[7] Images show the Q1 diaphram shutter used for digital cameras ES65, ES70, ES71 by Samsung. This shutter and similar shutters by other manufacturers are available on ebay and aliexpress.
[8] Arduino Mega Microcontroller, and Arduino Motor-Shield by Adafruit, version 1. Inexpensive units can be found on ebay and aliexpress.
[9] Test conditions: power 1 W, wavelength 1064 nm, duration 1 hour.
[10] Photodiode, Thorlabs PDA100A-EC, bandwidth 2.4 MHz.
[11] I/O-Device, National Instruments USB-6366.