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Low-cost mechanical shutter for light beams

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We present a simple design of a fast mechanical shutter for light beams using a low-cost personal computer loudspeaker. The shutter is capable of closing an aperture of 5 mm at a maximum speed of 1.7 mm/ms with a timing jitter of less than 10 μs. When combined with polarization optics, our device can also be used as an alterable switch and adjustable attenuator. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1520728]

Switching light beams with high speed and timing precision can be accomplished with electro-optical or acousto-optical modulators. These nonmechanical devices do not fully extinguish the light and provide only finite transmission. For infinite attenuation of a laser beam, mechanical shutters are the only option. Most widely known are iris shutters as used in photo cameras. In most cases, their unipolar design only allows one to switch the light beam either on or off with sufficient speed ($\sim$1 ms). Commercial shutters[1] without this deficiency are available at rather high cost ($\sim$\$1000). When placed in a laser laboratory, delicate optical devices such as interferometers might be perturbed by the acoustic vibrations created by the iris diaphragm. Mechanical shutters based on piezoelectric actuators have been demonstrated to achieve switching times of 10 μs, but the extinction ratio was limited to 300:1 for an aperture size of only 10 μm.[2] Chopper wheels permit exposure times of 10 μs for 1 mm slits but cannot be triggered asynchronously.[3–5] Shutters based on thermal expansion of Ni–Cr wires allow switching times of 100 μs for 1 mm slits but the repetition rate is limited to 5 s due to the thermal recovery time of the wire.[6]

We developed a simple bipolar mechanical shutter which combines fast switching, high timing precision, and ultimate extinction. The design is shown in Fig. 1. The device is based on a standard loudspeaker ($\sim$\$5) as used in personal computers. Loudspeakers with attached retroreflectors have already been used as pathlength varying elements in low-cost interferometric femtosecond autocorrelators.[7] In our design, all membranes are removed so that the voice coil freely moves out of the permanent magnet of the loudspeaker. A stiff nontransparent flag, which is attached to the top of the voice coil, serves as the movable beam stop. The flag is made of a light, nontransparent material (plastic or aluminum foil). The copper leads on the remaining membrane pieces of the loudspeaker are reinforced by glue. An upper mechanical stopper is mounted above the voice coil. To minimize acoustic noise, damping material (felt, in our design) is glued below the upper stopper and on top of the permanent magnet. A little hole is cut in the middle of the remaining membrane on top of the voice coil to further reduce acoustic noise and to increase speed. By minimizing the mass of the moving parts, we achieve high acceleration and low acoustic noise.

The driving circuit for the shutter device as depicted in Fig. 2 consists of four transistor switches. The supply voltage should range between 2 and 5 V and needs to support 500 mA. In order to accelerate the shutter in the desired direction, the supply voltage for the voice coil can be reversed by changing the transistor–transistor logic (TTL) level (low=0 V, high=5 V). A low TTL level switches transistors $Q2$ and $Q4$ to a conducting state and $Q1$ and $Q3$ to a nonconducting state. The situation is reversed for a high TTL level.

The motion of the flag was measured by shining an expanded laser beam (diameter 30 mm) through a vertical slit (horizontal width 2 mm and vertical width 10 mm) placed directly in front of the shutter device. The transmitted light intensity is measured with a photodiode. When the shutter vertically moves into the light beam (positive x direction), part of the expanded light beam is stopped by the flag so that the light intensity transmitted through the slit is proportional to the displacement of the flag. Knowing the maximum displacement (5.3 mm for our device), the relative displacement of the flag can be derived from the measured light intensity. The result of such a measurement is shown in Fig. 3. For $t<0$, the TTL signal connected to the driving electronics is set to high keeping the flag in the elevated position. The supply

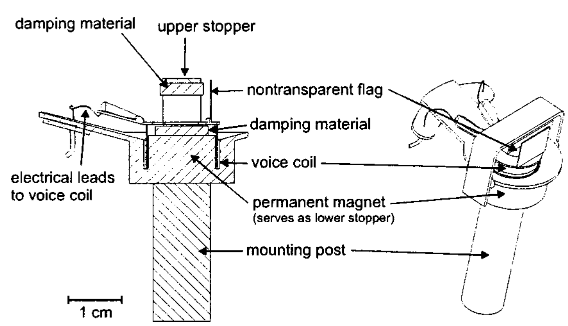

FIG. 1. Shutter design based on a standard loudspeaker as used in personal computers.

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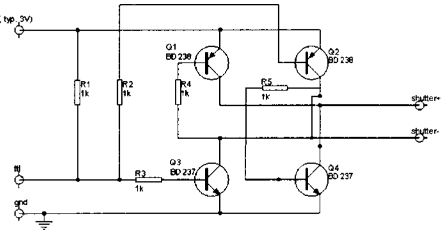

FIG. 2. Electric driving circuit of the shutter device.

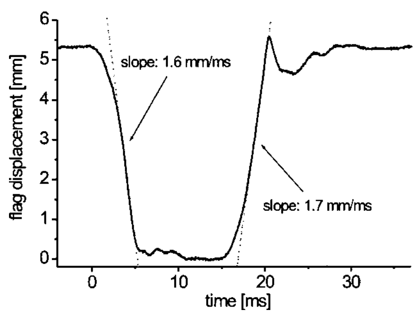

FIG. 3. Displacement of the shutter flag. At $t=0$ and $t=15$ ms, TTL input to the driving circuit was changed.

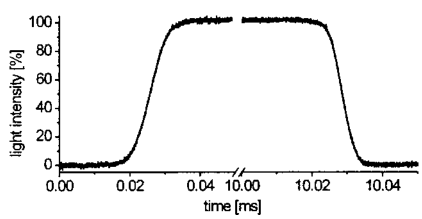

FIG. 4. Measurement of the extinction time. The flag is moved into ($t=0$) and out of ($t=10$ ms) the focus of a laser beam with 10 μm waist.

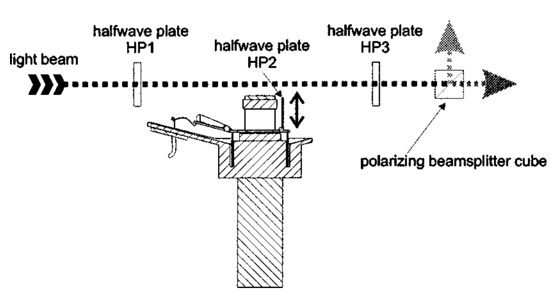

FIG. 5. Switchable attenuator for laser beams.

voltage is 4 V resulting in a current of 300 mA. At $t=0$, the level of the TTL signal was changed to low. As a consequence, the loudspeaker coil with the attached flag starts to accelerate into the negative x direction. After 2.5 ms, the flag has reached its final velocity of 1.7 mm/ms as derived by a linear fit to the displacement curve. At $t=5$ ms, the flag motion is stopped by the damping material on top of the permanent magnet. The vibrations caused by the stopping of the flag are damped within 5 ms. At $t=15$ ms, the TTL level is changed to high causing the flag to move into the positive x direction with similar characteristics. As an important feature of our design, the speed of the flag is equally high in the upward direction as in the downward direction.

For fast interruption of a laser beam, the shutter is placed in the focal plane of a lens. To provide a measure of typical shutter times, we have focused a laser beam to a waist of 10 μm. Figure 4 shows the light intensity measured while the shutter is opening and closing. Within 10 μs, the laser beam can be fully transmitted or extinguished. Due to the transverse Gaussian intensity distribution of the laser beam, the measured data are well described by an error function. For a known waist of the laser beam, the fit yields an independent measurement of shutter velocity. We find that 1.7 mm/ms is in agreement with the measurement discussed in the previous paragraph. The delay to the electronic TTL signal is 3.5 ms with a jitter of less than 10 μs. The minimum delay between an opening and closing pulse applied to the shutter is determined by the time that the flag has come to a complete rest (roughly 5 ms, see Fig. 3). In order to create controlled light pulses with duration down to 50 μs, one may place two shutters in series. Trigger pulses are applied to each shutter in such a way that the first shutter opens the beam at a given time while the second one interrupts it after the duration time.

We also employ our fast switching device to place optical elements into the light beam, like, e.g., a waveplate or a grayfilter. In this way, one creates optical switches or switchable attenuators. Instead of the flag, the optical element is simply glued on the movable loudspeaker coil. A switchable rotation of polarization is realized by moving a halfwave plate into a light beam with linear polarization. The rotation angle of the polarization is twice the angle between the polarization and the optical axis of the halfwave plate. If the light polarization is turned by 90° the light beam can be switched between two ports of a polarizing beam splitter.

Since the waveplate has to be glued to the loudspeaker coil, it can no longer be freely rotated. This limitation can be overcome by placing the movable halfwave plate HP2 between two stationary, but rotatable, halfwave plates HP1 and HP3 as schematically depicted in Fig. 5. The light transmitted through the polarizing beam splitter can then be switched between two freely adjustable intensity levels. The first intensity level (without HP2 in the beam) is set by rotating the halfwave plates HP1 and HP3. Note, that for two halfwave plates placed in series, the total rotation angle of the polarization is determined only by the difference of the rotation angles of the two waveplates. The second intensity level is then adjusted by moving HP2 into the beam and simultaneously rotating HP1 and HP3 by equal angles, thus keeping the difference angle between HP1 and HP3 constant. In this way, the intensity switch replaces considerably more expensive devices such as electro-optic modulators.

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