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ABSTRACT

We have developed a low-cost mechanical shutter driver with integrated arbitrary waveform generation for optical switching and control using a programmable system-on-chip device. This microcontroller-based device with configurable digital and analog blocks is readily programmed using free software, allowing for easy customization for a variety of applications. Additional digital and analog outputs with arbitrary timings can be used to control a variety of devices, such as additional shutters, acousto-optical modulators, or camera trigger pulses, for complete control and imaging of laser light. Utilizing logic-level control signals, this device can be readily integrated into existing computer control and data acquisition systems for expanded hardware capabilities.

I. INTRODUCTION

Mechanical shutters are utilized for optical switching of laser light in applications requiring complete extinction of the light. For example, multiple shutters are used in ultracold atomic physics experiments where even low levels of background light can cause heating of atomic samples.[1] Due to the high costs of these experiments,[2] high-precision commercial systems are not readily accessible for typical laboratories, especially at undergraduate-only institutions. As such, a variety of low-cost homemade shutters and drivers have been developed. Examples include shutters designed using a personal computer speaker, 3D printed blades mounted on a DC motor, and a piezoelectric cantilever actuator, among others.[3–7] Acharya *et al.* developed a universal driver circuit for use with homemade shutters.[8]

Mechanical shutters can be slow (>10 μs) for many applications, though. Alternatively, acousto-optical modulators (AOMs) with higher switching speeds can be used to generate short pulses (≥25 ns), as well as being used as frequency shifters.[9–11] AOMs may not provide sufficient extinction of resonant laser light and are often used in laser cooling and trapping experiments in conjunction with mechanical shutters to provide fast optical switching with reduced background light.

Many experiments, particularly in the area of ultracold atomic physics, are shot-based, where a single shot comprises of timed analog and digital outputs to control devices such as mechanical shutters, AOMs, and camera triggers in an automated sequence. Parameters, such as digital pulse delay or voltage ramps, are often varied from shot-to-shot. In our experimental sequence for absorption imaging of ultracold atoms, for example, a mechanical shutter opens briefly to allow for several 200-μs pulses of resonant light generated by an AOM to detect the atom cloud and to be imaged at a variable time with a camera triggered by a control signal.[2] Commercial and open-source software utilized with data acquisition hardware is available.[12–15] Additionally, the optimization of parameters, such as laser intensity and frequency detuning, is beneficial in atomic cooling experiments and is aided by arbitrary waveform generation. Arbitrary waveform generators (AWGs) have been developed using field-programmable gate array (FPGA) technology for experiments with atomic clocks and trapped ions.[16–18] AWGs have been used to produce nonlinear frequency-chirped light for coherent control of ultracold collisions and for optimal control of quantum systems.[19–21]

We have designed and built a microcontroller-based shutter driver circuit with an integrated arbitrary waveform generator for optical switching of light to be used in ultracold atomic physics experiments. This device provides comparable shutter driver performance characteristics of a commercially available device but with additional functionality and customizability at a fraction of the cost. The heart of this design is a 32 bit programmable system-on-chip PSoC 4 ARM Cortex-M0 series single-core microcontroller developed by Infineon Technologies.[22] PSoCs are programmed using a free integrated development environment (IDE), allowing the output waveform to be adjusted for any mechanical shutter, making for easy integration into existing systems. A PSoC consists of a core and programmable routing and interconnects. Unlike other microcontrollers, it consists of configurable analog and digital blocks. This allows for most of the design and functionality of the circuit to be configured rapidly through software replacing bulk electronics components in a reconfigurable and small footprint format. The array of digital and analog outputs with arbitrary timings can be used to control a variety of devices, such as additional shutters, AOMs, or camera trigger pulses, for complete control of optical switching and imaging of laser light. Utilizing logic-level control signals, this device can be readily integrated into existing computer control and data acquisition systems for expanded hardware capabilities. Modules by Avnet and Digilent have been previously implemented in other control applications.[23,24]

II. CIRCUIT DESIGN

A. Shutter driver programming and block diagram

The PSoC-based shutter controller described here was used with an NM Laser LST400 mechanical shutter. This solenoid-driven shutter with an 8-mm aperture consists of an over-coated aluminum mirror designed for laser power handling up to 50 W. The NM Laser commercial controller can drive up to four LST400 shutters but without independent control and costs ~$700 USD. Comparatively, the PSoC is the most expensive component in our design at ~$15 for a PSoC 4 development board and even less for the surface mount packaging, while offering greater flexibility. For the design and prototyping of our circuit, a CY8KIT-049-4200 development board was used.

The timing capabilities of the PSoC provide customizability to be integrated into circuit designs for use with other commercial or homemade shutters to allow for complex timings of those devices or the added functionality, such as the arbitrary waveform generator (AWG) described in Sec. C, provided by the PSoC's configurable digital and analog blocks, counters, and clocks. The PSoC's on-board set of logic gates, comparators, and operational amplifiers can reduce the need for bulk components in circuit designs. The timings, voltages, and hardware used in our design were chosen to meet the specifications of the LST400 to provide comparable shutter performance with the available commercial driver and may need to be modified for use with other mechanical shutters or to meet specific user performance needs. To demonstrate the PSoC's flexibility, we have used it to control a mechanical shutter made from a personal computer loudspeaker.[3]

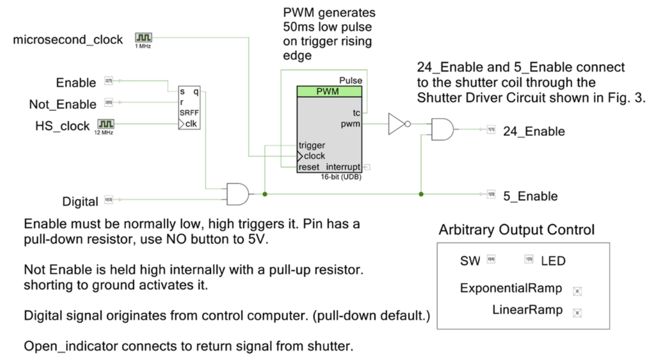

FIG. 1. The PSoC logic block diagram. The PSoC controls the timings for the 24 V, 50 ms capacitor discharge pulse and the 5 V hold signal for shutter operation. The shutter opens when the control signal goes HIGH and remains open for the duration of the control signal pulse. A set-reset flip-flop (SRFF) enables and disables the device and can be used as a safety interlock for a high-power laser.

The LST400 requires a 24 V, 50 ms pulse from a discharge capacitor to open the shutter coil and only 5 V applied across the coil to hold the shutter open (24 V may be applied to hold the shutter open but at the risk of damaging the shutter coil). The timings of these signals are controlled by the PSoC. The PSoC IDE uses a visual block diagram, as shown in Fig. 1, to program the transistor gate logic, while the code written in C++ is used to write commands, start clocks, and initialize blocks.

Three transistor-transistor logic (TTL)-level input signals pass into the chip, seen on the left side of Fig. 1. A safety interlock is created via a set-reset flip-flop (SRFF). The *Enable* and *Not_Enable* signals feed into the set (s) and reset (r) inputs of the SRFF, respectively. The output q of this SRFF is sent to an AND gate along with the *Control_Signal* sent from a pulse generator or control computer to enable or disable the operation of the shutter. *Not_Enable* is held high internally with a pull-up resistor and shorting to ground activates it. A HIGH *Not_Enable* signal closes the shutter and prevents it from reopening. A HIGH *Enable* signal will reactivate the circuit, allowing for a subsequent HIGH *Control_Signal* to reopen the shutter.

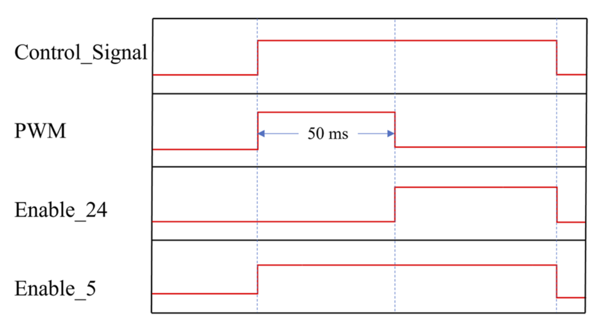

FIG. 2. PSoC timing diagram. The *Control_Signal* triggers the PWM output, while a combination of NOT and AND gates creates the 50-ms LOW *Enable_24* signal for the capacitor discharge pulse. *Enable_5* allows 5 V to be applied across the shutter after the capacitor discharges to hold the shutter open.

With the device enabled, the *Control_Signal* triggers a pulse width modulation (PWM) output and sends the 5-V TTL *Enable*_5 signal to open the shutter, as shown in the timing diagram in Fig. 2. The shutter remains open, while the *Control_Signal* remains HIGH. To do this, the PWM output remains HIGH for 50 000 pulses of the 1 MHz clock. This PWM signal is sent through a NOT gate and then an AND gate with *Enable*_5. This causes *Enable*_24 to continue to be LOW for 50 ms, while *Control_Signal* and *Enable*_5 are HIGH. While *Enable*_24 is LOW, the capacitor is discharged, opening the shutter. After the PWM counts off 50 ms, *Enable*_24 returns to HIGH, and *Enable*_5 is left HIGH to hold the shutter open, while the *Control_Signal* is HIGH.

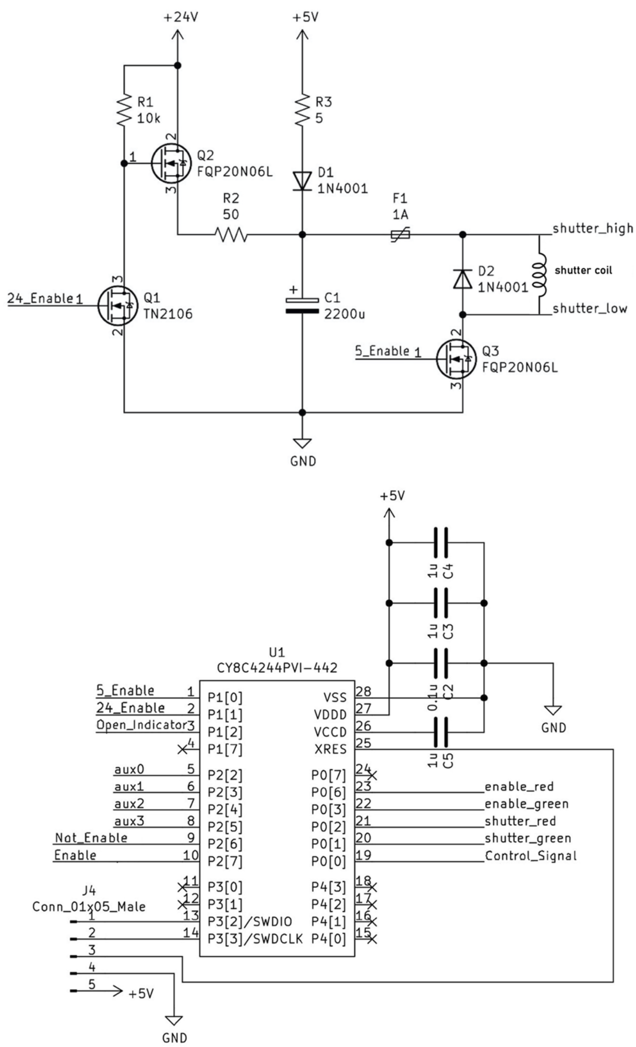

FIG. 3. Shutter driver circuit schematic. The *Enable*_24 and *Enable*_5 signals control two MOSFET switches *Q*1 and *Q*3, respectively, according to the timing diagram shown in Fig. 2. With *Q*1 open for 50 ms, Q2 remains closed to allow for a 2200 μF capacitor to discharge through the shutter coil, opening it. After this time, Q1 closes, grounding the drain and, therefore, opening Q2. A 5-V supply holds the shutter open.

B. Shutter driver circuit

The shutter driver circuit diagram for our compact printed circuit board (PCB) design is shown Fig. 3. A 2200 μF capacitor is charged via a 24 V supply. The timed *Enable*_24 and *Enable*_5 signals from a CY8C4244PVI-442 surface mount PSOC 4 toggle MOSETs Q1 and Q3, respectively, to control the 24- and 5-V supply voltages according to the timing diagram in Fig. 2. With *Q*1 open for 50 ms, Q2 remains closed to allow for a 50-ms discharge pulse through the shutter coil, opening it. After this time, *Q*1 closes, grounding the drain and, therefore, opening Q2. A 5-V supply holds the shutter open, reducing heating of the coil. The capacitor is charged when the shutter closes.

C. Arbitrary waveform generator programming and analog output block diagram

The PSoC 4's configurable analog and digital blocks, clocks, and general purpose input/outputs (GPIOs) (up to 98 on some models) allow for accurate and arbitrary timing sequences. In our PCB shutter driver design, 12 GPIOs remain available to interface with other devices. We use the PSoC to generate arbitrary digital output pulse sequences. In general, this can be accomplished either through hardware configuration via the PSoC visual block diagram or through the software code. However, as much of the hardware resources are allocated to the shutter controller in our design, adding a second PWM output through hardware for this purpose was not possible on this particular chip, and the arbitrary pulse sequence was coded

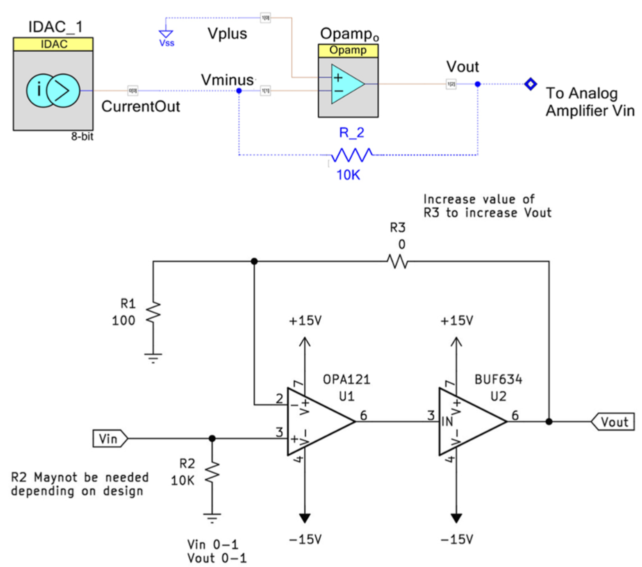

FIG. 4. Analog current-to-voltage converter visual block diagram and buffered output circuit. Top: A current digital to analog converter (IDAC) is assigned to a GPIO pin and outputs an analog current signal that is coded in software. The IDAC output is connected to an onboard operational amplifier as a current-to-voltage converter to provide an analog voltage output with a 0–1 V range. Blue wires represent off-board connections. Bottom: The analog output of the PSoC is sent to an OPA121 operational amplifier and a BUF634 high-speed buffer to provide sufficient current to drive the 50-Ω analog modulation input of an acousto-optical modulator (AOM) driver.

through software, instead (additional simple digital outputs created through hardware are still possible, though). Software coding for this is straightforward. We chose to trigger the arbitrary digital output signal with an external TTL pulse into a separate digital input independent of that used for the shutter *Control_Signal*.

An analog voltage output is achieved using a configurable analog block. The visual block diagram is shown in Fig. 4. An 8-bit current digital to analog converter (IDAC) is assigned to a GPIO pin and outputs an analog current signal that is coded in software. The maximum current out of the IDAC is 612 μA. The IDAC output pin is externally connected to an onboard operational amplifier as a current-to-voltage converter to provide an analog voltage output. The desired voltage range is achieved with the appropriate choice of current range and external resistors. In our case, we choose to set a 0–1 V output voltage range to match that of the amplitude modulation input of our AOM drivers. To supply enough current to drive this 50-Ω input, the voltage output of the onboard operational amplifier is sent to a OPA121 operational amplifier and a BUF634 250 mA, unity-gain high-speed buffer.

Arbitrary analog sequences are achieved via software code to control the IDAC and are externally triggered via a separate TTL pulse. To create time-varying waveforms, the IDAC is programmed to increase or decrease by small intervals according to a given waveform after a set timing delay within a loop. The step size is limited by the 1 MHz clock chosen. A waveform can be triggered once or repeat indefinitely, and arbitrary analog waveforms can be easily coded.

III. PERFORMANCE AND CHARACTERISTICS

A. Shutter driver performance

To measure the shutter driver performance, light from a He:Ne laser expanded to a 4.2-mm $1/e^2$ beam diameter is centered on the 8 mm LST400 shutter aperture and measured with a photodetector, as shown in Fig. 5. A pulse generator provides the control signal for the shutter driver, and the control signal and resulting photodetector signal are measured.

The input *Control_Signal* and the transmission signal from the photodetector are shown in Fig. 6. Our driver circuit is able to operate LST400 with performance characteristics comparable to the manufacturer's specifications when operated with the commercial unit. The delay between the *Control_Signal* and the start of the transmission of the light through the shutter is ~20 ms with a rise time to fully open of ~10 ms for a 4.2-mm-diameter beam with a measured shutter speed of 0.48 mm/ms. Shorter delay times are achievable with a larger discharge capacitor (e.g., 4700 μF) but at the expense of additional mechanical vibration. It takes ~13 ms from the end of the control signal to fully extinguish the light with a fall time of ~5.5 ms. The minimum achievable pulse width was 33.6 ms at full width at half maximum (FWHM), and a maximum repetition rate of 2.3 Hz is achieved.

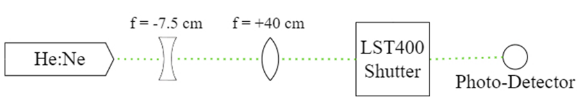

FIG. 5. Shutter driver performance test setup: Light from a He:Ne laser is expanded with a telescope to fill the aperture of the shutter. The transmission signal obtained by using the photodetector along with the control signal is measured.

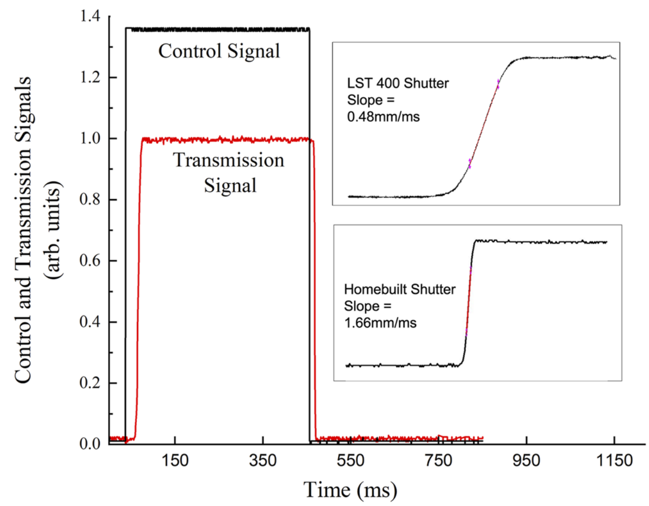

FIG. 6. Control and transmission signals. Typical control and transmission signals are shown, with ~20 and ~10 ms between control signal HIGH and LOW and the beginning of the rising and falling of the transmission signal, respectively. Upper inset: The LST shutter speed is measured to be 0.48 mm/ms. Lower inset: A homebuilt shutter using a personal computer loudspeaker controlled by the PSoC has a speed of 1.66 mm/ms.

To demonstrate the flexibility of the PSoC, we constructed a mechanical shutter utilizing a personal computer loudspeaker as developed by Singer *et al.*[3] The membranes were removed so that the voice coil was allowed to freely move out of the permanent magnet. A thin, stiff piece of foil was used as a moveable flag and was glued to the top of the voice coil. A metal stop was mounted above the coil. With the homemade mechanical shutter inserted in our test setup, we measure a shutter speed of 1.66 mm/ms, as shown in the lower inset in Fig. 6, consistent with the results presented by Singer *et al.*[3] We attribute the faster shutter speed to the reduced mass of the foil beam stop compared to the aluminum mirror of the LST400.

B. Arbitrary waveform generator output

To demonstrate the added functionality of our device, we have programmed digital and analog output sequences that are externally triggered by TTL pulses. The timing resolution of these sequences is limited by the 1 MHz internal clock chosen. An arbitrary TTL-level, digital output pulse-burst sequence consisting of a 10 μs pulse, a pair of 20 μs pulses, and a 30 μs pulse separated by 20 μs is shown in Fig. 7 after a 30 μs programmed delay. A minimum delay between the digital control signal and the pulse burst was found to be ~3 μs, and we have been able to reliably produce pulses as short as ~3 μs controlled by the PSoC microcontroller in addition to the much shorter pulses available when using the PSoC programmable-logic features. A maximum repetition rate of 167 kHz is achieved.

An arbitrary analog output sequence is also demonstrated, as shown in Fig. 8. The IDAC output is programmed for a series of analog output ramps that increase quadratically with time for 150 μs

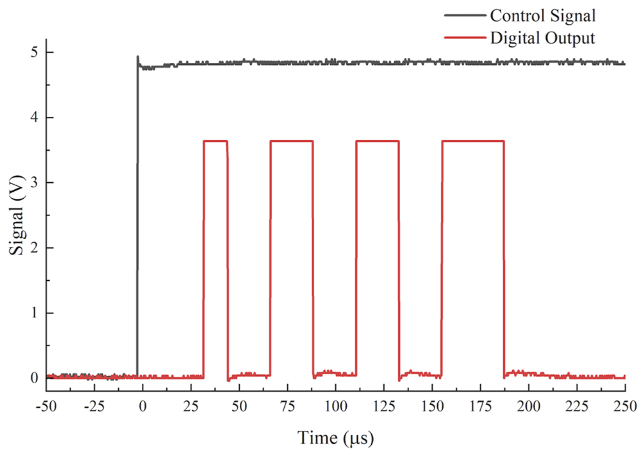

FIG. 7. Arbitrary digital output. An external TTL pulse triggers an arbitrary digital pulse burst consisting of a 10 μs pulse, a pair of 20 μs pulses, and a 30 μs pulse after a 30 μs programmed delay.

in 10 μs steps until reaching 50 μA corresponding to a 0.5 V output (the maximum voltage output of 1 V is achieved at the 100 μA limit). The step size can be reduced further if necessary but is limited by the clock frequency chosen, in our case 1 MHz. A delay of 20 μs between the external trigger pulse and the analog output signal is programmed. A ~1 μs shot-to-shot variation in delay between the external trigger pulse and the beginning of either the digital or analog output sequences is measured. We attribute this to the variation in phase between the external trigger signal and the internal 1 MHz clock. We have measured analog output pulses as short as 4 μs at FWHM for a maximum repetition rate of 125 kHz.

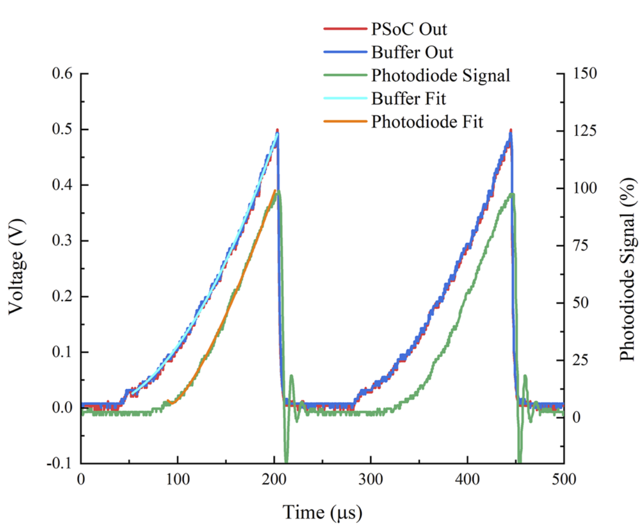

FIG. 8. Arbitrary analog output. The PSoC analog output (red) is programmed with a series of ramps varying quadratically with time that are sent into a high-speed analog buffer. The buffered output signal (blue) is sent to the 50-Ω analog modulation input of an AOM driver. The resulting first-order diffracted light beam from the AOM is measured on a photodiode (green) and is modulated from 0% to 100%. Least-squares power law fits yield exponents of 1.94 ± 0.12 and 1.60 ± 0.01 for the buffered signal (teal) and optical signal (orange), respectively.

The analog output is sent to the unity-gain buffer, which faithfully reproduces the voltage ramp as shown in Fig. 8 but with sufficient current for the 50-Ω amplitude modulation input of an AOM driver. A least-squares power law fit of the buffer output signal gives an exponent of 1.94 ± 0.12. The output is sent to the analog amplitude modulation input of an AOM driver (Gooch & Housego, PN +AODR 1080AF-AEN0-2.0), and the resulting first-order diffracted beam out of the AOM (Gooch & Housego, PN AOMO 3080-125 442-633NM 2MM) is measured with a photodiode with respect to time. The resulting photodiode signal is shown in Fig. 8, modulated from 0% to 100% quadratically over 150 μs. A least-squares fit of the photodiode signal yields an exponent of 1.60 ± 0.01. We attribute the deviation from the desired quadratic function to the response of the AOM. However, this can be corrected by adjusting the programmed waveform accordingly.

Both the minimum analog and digital pulse widths are significantly shorter than the pulse length needed for absorption imaging in our cold atom experiments (typically on the order of 200 μs). The sequences are consistent and highly reproducible on the timescales that we are interested in for our experiments. As such, this PSoC-based device is capable of controlling various devices, such as additional shutters, acousto-optical modulators, and camera trigger pulses needed for optical switching, as well as intensity and frequency modulation of laser light and imaging of cold atoms.

IV. CONCLUSION AND OUTLOOK

We have developed a low-cost shutter driver and arbitrary waveform generator for optical switching and intensity modulation of laser light using a programmable system-on-chip (PSoC) device. The PSoC's configurable digital and analog blocks allow for easy customization and flexibility while limiting the number of discrete components. This simplifies the circuit design and reduces the cost and overall footprint of finished designs, allowing them to be incorporated into existing experimental setups to expand analog and digital input and output capabilities or replace tradition data acquisition boards in some applications. Their compact design and low power consumption make them ideal for use in remote applications. Although suitable for many applications, the PSoC 4 has a limited feature set. Future designs will utilize the configurable analog subsystem and higher clock frequency of the PSoC 5 architecture. This chip (which was not available to us at the time of this writing) has greater hardware capabilities, such as analog voltage and waveform outputs, operational amplifiers, and comparators, and will be suitable for complex timing sequences, such as those used in experimental ultracold atomic physics.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

J. M. Craven: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Software (lead); Writing – original draft (equal); Writing – review & editing (supporting). **E. Meeks**: Data curation (equal); Investigation (supporting); Software (supporting). **G. Delich**: Data curation (supporting); Investigation (supporting); Writing – original draft (supporting). **E. Ayars**: Resources (supporting); Software (supporting). **H. K. Pechkis**: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (lead); Project administration (equal); Resources (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **J. A. Pechkis**: Conceptualization (lead); Data curation (equal); Formal analysis (equal); Investigation (equal); Project administration (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] R. Grimm, M. Weidemüller, and Y. B. Ovchinnikov, "Optical dipole traps for neutral atoms," Adv. At., Mol., Opt. Phys. **42**, 95–170 (2000).
[2] H. J. Lewandowski, D. M. Harber, D. L. Whitaker, and E. A. Cornell, "Simplified system for creating a Bose–Einstein condensate," Journal of Low Temperature Physics **132**(5), 309–367 (2003).
[3] K. Singer, S. Jochim, M. Mudrich, A. Mosk, and M. Weidemüller, "Low-cost mechanical shutter for light beams," Rev. Sci. Instrum. **73**, 4402–4404 (2002).
[4] G. H. Zhang, B. Braverman, A. Kawasaki, and V. Vuletić, "Note: Fast compact laser shutter using a direct current motor and three-dimensional printing," Rev. Sci. Instrum. **86**, 126105 (2015).
[5] W. Bowden, I. R. Hill, P. E. G. Baird, and P. Gill, "Note: A high-performance, low-cost laser shutter using a piezoelectric cantilever actuator," Rev. Sci. Instrum. **88**, 016102 (2017).
[6] C. S. Adams, "A mechanical shutter for light using piezoelectric actuators," Rev. Sci. Instrum. **71**, 59 (2000).
[7] L. P. Maguire, S. Szilagyi, and R. E. Scholten, "High performance laser shutter using a hard disk drive voice-coil actuator," Rev. Sci. Instrum. **75**, 3077 (2004).
[8] A. Acharya, S. De, P. Arora, and A. Sen Gupta, "A universal driver for vibration free operation of mechanical shutters," Measurement **61**, 16–20 (2015).
[9] P. D. Lett *et al.*, "Observation of atoms laser cooled below the Doppler limit," Phys. Rev. Lett. **61**, 169–172 (1988).
[10] M. Kasevich and S. Chu, "Laser cooling below a photon recoil with three-level atoms," Phys. Rev. Lett. **69**, 1741–1744 (1992).
[11] W. J. Schwenger and J. M. Higbie, "High-speed acousto-optic shutter with no optical frequency shift," Rev. Sci. Instrum. **83**, 083110 (2012).
[12] A. Keshet and W. Ketterle, "A distributed, graphical user interface based, computer control system for atomic physics experiments," Rev. Sci. Instrum. **84**, 015105 (2013).
[13] P. T. Starkey, C. J. Billington, S. P. Johnstone, M. Jasperse, K. Helmerson, L. D. Turner, and R. P. Anderson, "A scripted control system for autonomous hardware-timed experiments," Rev. Sci. Instrum. **84**, 085111 (2013).
[14] See URL https://www.ni.com/en-us/shop/labview.html for Labview.
[15] See URL https://m-labs.hk/experiment-control/artiq/ for m-labs.
[16] S. Donnellan, I. R. Hill, W. Bowden, and R. Hobson, "A scalable arbitrary waveform generator for atomic physics experiments based on field-programmable gate array technology," Rev. Sci. Instrum. **90**, 043101 (2019).
[17] M. T. Baig, M. Johanning, A. Wiese, S. Heidbrink, M. Ziolkowski, and C. Wunderlich, "A scalable, fast, and multichannel arbitrary waveform generator," Rev. Sci. Instrum. **84**, 124701 (2013).
[18] R. Bowler, U. Warring, J. W. Britton, B. C. Sawyer, B. C. Sawyer, and J. Amini, "Arbitrary waveform generator for quantum information processing with trapped ions," Rev. Sci. Instrum. **84**, 033108 (2013).
[19] J. A. Pechkis, J. L. Carini, C. E. Rogers, P. L. Gould, S. Kallush, and R. Kosloff, "Coherent control of ultracold ^{85}Rb trap-loss collisions with nonlinearly frequency-chirped light," Phys. Rev. A **83**, 063403 (2011).
[20] C. Brif, R. Chakrabarti, and H. Rabitz, "Control of quantum phenomena: Past, present and future," New J. Phys. **12**, 075008 (2010).
[21] S. Rosi, A. Bernard, N. Fabbri, L. Fallini, C. Fort, M. Inguscio, T. Calarco, and S. Montangero, "Fast closed-loop optimal control of ultracold atoms in an optical lattice," Phys. Rev. A **88**, 021601(R) (2013).
[22] See URL https://www.infineon.com/dgdl/Infineon-PSoC_Brochure-Product Brochure-v01_00-EN.pdf?fileId=8ac78c8c7d0d8da4017d0f64d206504e&utm_source=cypress&utm_medium=referral&utm_campaign=202110_globe_en_all_integration-product_brochure for Infineon.
[23] A. Sitaram, G. K. Campbell, and A. Restelli, "Programmable system on chip for controlling an atomic physics experiment," Rev. Sci. Instrum. **92**, 055107 (2021).
[24] A. Trenkwalder, M. Zaccanti, and N. Poli, "A flexible system-on-a-chip control hardware for atomic, molecular, and optical physics experiments," Rev. Sci. Instrum. **92**, 105103 (2021).