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High-speed acousto-optic shutter with no optical frequency shift

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Acousto-optic modulators are widely used for rapid switching and shuttering of laser beams. In many applications, the concomitant frequency shift is undesirable and must be compensated for elsewhere in the system. Here we present a simple method of achieving rapid laser power switching without an accompanying laser frequency shift. The demonstrated acousto-optic shutter achieves a switching time of around 25 ns, an extinction ratio of 46 dB, and efficiency comparable to a conventional double-pass acousto-optical modulator configuration. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4746292]

I. INTRODUCTION

Electronically controlled laser-beam shutters are a basic tool in a wide range of optical sciences, allowing complex experimental sequences involving multiple laser beams and serving functions as diverse as blocking beams for safety,[1,2] "picking" pulses from pulsed lasers,[3] and transmitting controlled pulses for high-speed imaging.[4,5] Various technologies have been employed for on-off switching of laser beams, including mechanical-vane, electro-optic, and acousto-optic shutters. Mechanical shutters are an attractive solution at low frequencies and when extremely high contrast between on-state and off-state transmission is required. Electro-optic shutters can switch very rapidly,[6] but are relatively expensive, typically require either high drive voltage or wave-guide operation (with the associated insertion loss), and often display considerable parameter drift.[7] Acousto-optical crystals are an attractive alternative in many applications, competing favorably with electro-optic shutters in robustness, thermal stability, extinction ratio, and cost, while providing substantially higher speed than mechanical shutters.

The availability of acousto-optic modulators (AOMs) as commercially pre-packaged, modular devices has facilitated their widespread use in atomic, molecular, and optical physics; in experiments from laser cooling and trapping (e.g., Refs. 8 and 9) to atomic clocks (e.g., Refs. 10 and 11) and atomic magnetometers (e.g., Ref. 12), AOMs play a key role in the control of laser frequency and power. In atomic-physics and spectroscopic applications, the frequency shift of the AOM, of order 100 MHz, is generally much larger than the precision with which the laser frequency must be controlled. While the ability to shift the optical frequency is often extremely useful, in some cases a rapid shutter with high extinction in the off state is more desirable, for instance, when laser light is needed at the frequency of the same atomic line to which the laser frequency is stabilized or when multiple lasers beams at the same optical frequency are derived from a single laser oscillator but must be switched on and off separately. The apparatus described in the present manuscript was motivated, for example, by a pump-probe atomic magnetometry experiment, in which the laser is locked at an optimal wavelength and the magnetic field is determined by modulating the pump laser beam power near the Larmor frequency of an atomic sample, while a probe beam at the same laser frequency remains unmodulated. Similarly in ultra-cold-atom experiments, it is not uncommon to split a single laser beam into multiple independently switchable beams at the same frequency (e.g., probe beams for imaging and "blast" beams for removing unwanted hyperfine components, or repumping laser beams for magneto-optical trapping and for imaging). In such experiments, the ability to switch a laser beam without shifting it offers an additional degree of freedom in the design of the laser system.

AOMs are often operated in a double-pass configuration,[13,15] in which the frequency shift of the laser is doubled, and the angular deflection is canceled, independent of frequency. In the present work, we present an alternate family of double-pass configurations of a free-space acousto-optic modulator in which both the frequency shift and the angular shift are canceled out.[14] This simple and easily implemented technique allows independent direct control of the laser power with no change in the in-going light frequency, permitting the AOM to be used in the same way as a mechanical shutter, but at much higher speed.

II. PRINCIPLE OF OPERATION

The acousto-optic effect can be viewed as Bragg diffraction of light from a moving acoustic compression wave, or alternatively as absorption/emission of crystal phonons by the optical field. To obtain significant angular deflection of the diffracted laser beam, the acoustic wavelength must be comparable in magnitude to the optical wavelength; consequently the acoustic frequency must be high (on the order of 100 MHz). By energy conservation (in the phonon-absorption picture) or, equivalently, by an analysis of reflection from a moving grating, it is seen that the diffracted beam differs in frequency from the input beam by this RF acoustic frequency. Depending on whether the reflection occurs from the Bragg planes of a receding or approaching density grating, the diffracted beam is either down-shifted or up-shifted by the RF acoustic frequency.

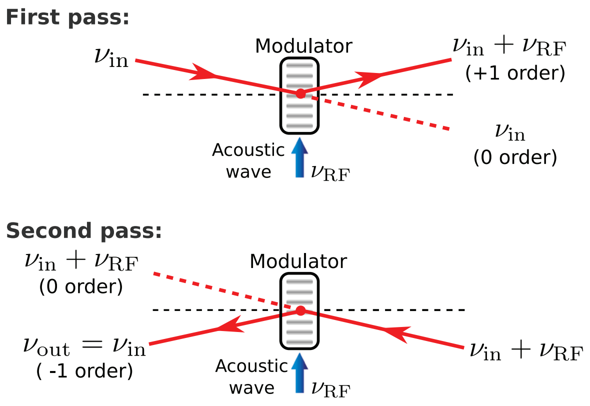

FIG. 1. Cancellation of frequency shift by double-passing in opposite diffraction orders. Light in positive diffraction orders is blue-shifted relative to the input, while light in negative orders is red-shifted. By arranging a second pass through the same modulator such that the input to the second pass is approximately anti-parallel to the zeroth order of the first pass, zero net frequency shift is obtained.

By double-passing the laser beam through the acousto-optical crystal in such a way that the output beam experiences positive first-order Bragg diffraction on the first pass and negative first-order diffraction on the second pass, we obtain zero net frequency shift. As can be seen from the diagram in Fig. 1, this combination requires that the returning diffracted beam not retrace its path, but instead follow a path that is the mirror reflection of its previous path about the Bragg plane. To good approximation, this implies that the returning diffracted beam must be counterpropagating with the undiffracted first-pass laser beam; as a result the output beam would contain a contribution not only from the $(+1, -1)$ orders but also from the (0, 0) orders, where (m_1, m_2) indicates the order of diffraction on the first and second passes, respectively. To prevent transmission of the unshifted orders and allow high extinction of the laser beam, we cannot simply block the zeroth order beam, as this would also block the desired beam. Instead, we employ a half wave plate and polarizer. The positive first-order diffracted beam first encounters the wave plate, which rotates its linear polarization to the transmission axis of the polarizer, while the zeroth-order beam is blocked by the polarizer. Unlike the standard double-pass configuration in which the out-going and in-going laser beams counterpropagate along the same path, this configuration produces an output laser beam spatially separated from the input beam; consequently no polarization optics are required at the output, an edge mirror being sufficient to isolate the out-going light. It should be noted that light not diffracted on the second pass does counterpropagate along the input laser beam path; since this light is orthogonally polarized, however, it may be easily rejected with an ordinary polarizer.

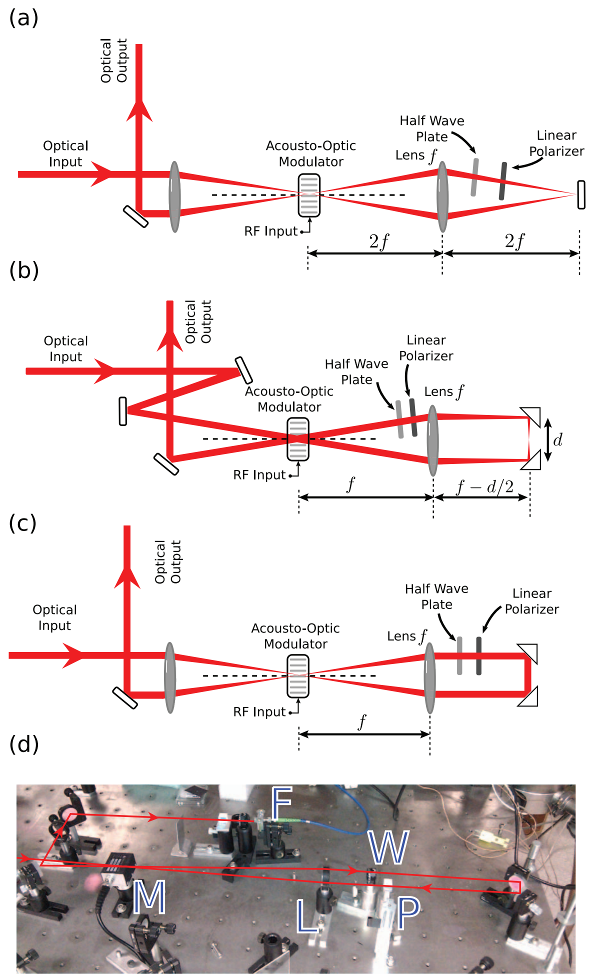

FIG. 2. Three practical realizations of the frequency-shift-canceling double pass configuration. In configuration (a), an input lens focuses laser light into the acousto-optic crystal, and a second lens placed at twice its focal length images the laser beam waist onto a retroreflecting mirror and then back onto the crystal at the appropriate angle for Bragg reflection into the negative order. In configuration (b), collimated light enters the crystal, and a lens one focal length away combines with a pair of mirrors in the periscope configuration to accomplish a similar reflection. In configuration (c), laser light is focused on the crystal and re-collimated by a lens one focal length away. A pair of periscopic mirrors retroreflects the beam with a lateral shift, so that it re-traces in reverse the path of the first-pass zeroth order beam. The photograph (d) shows the actual experimental setup in configuration (c), indicating AOM (M), lens (L), wave plate (W), polarizer (P), and the fiber (F) into which the light was coupled.

III. APPARATUS

Laser light for testing the shutter was obtained from an external-cavity diode laser operating at 780 nm. The shutter consisted of an AOM (NEOS 15210) driven by a RF source (Minicircuits POS-400 voltage-controlled oscillator) followed by an amplifier (Minicircuits ZHL-1-2W) and gated by a high-speed RF switch (Minicircuits ZYSW-2-50DR). Three versions of the acousto-optic shutter are shown schematically in Fig. 2, along with a photograph of the apparatus employed in the measurements. In each version, the first-order diffracted laser beam from the AOM was made to retrace not its own path, but that of the undiffracted zeroth-order beam, which is to good approximation the mirror image of the first-order diffracted beam path about the Bragg planes of the acoustic wave in the crystal. (Mathematically, this is equivalent to saying that the transverse component of the laser wave vector, i.e., the component parallel to the acoustic-wave propagation direction, is made to change sign.) This transverse reflection was achieved either with a lens, by imaging the beam waist in the crystal onto a mirror and then back onto the same spot in the crystal (panel (a) in the figure), or alternatively by means of a pair of 45° mirrors (panels (b) and (c) in the figure). The configurations labeled (a) and (c) are desirable when the in-coupled laser beam needs to be focused into the AOM, for instance, to improve the overlap of the laser beam with the active region of the modulator, to improve modulation bandwidth by providing a greater spread of transverse wave-vector components, or to minimize the turn-on time of the shutter; conversely configuration (b) is useful when it is desirable to couple a nearly collimated beam into the modulator, e.g., to improve diffraction efficiency or to minimize the number of optical surfaces traversed. In practice, the configurations with a pair of 45° mirrors were found to be somewhat more convenient to align because of the finely controlled degrees of freedom afforded by standard mirror mounts.

In addition to the shutter itself, small amounts of laser light were picked off both before and after the acousto-optic shutter and sent to two separate saturated-absorption cells of rubidium for characterization of the optical frequency shift. Optionally, the output light was also sent to a fast photodiode (Panasonic PNZ331CL, reverse biased by 9 V and terminated by 50 Ω) to characterize the shutter switching speed, as described below.

IV. PERFORMANCE

We have characterized the switching speed, efficiency, and extinction of this shutter, and compared the input and output optical frequencies. A comparison of saturated-absorption spectra before and after the acousto-optic shutter is shown in Fig. 3. By fitting each spectrum in the neighborhood of a given peak to the sum of a Lorentzian function and a second-order polynomial (to account for the background Doppler spectrum), we can determine the frequency difference before and after the AOM for each peak, using the known line splittings as a frequency calibration. In particular, such fits were performed for the $F = 2 \rightarrow F' = 3$ direct line, the $F = 2 \rightarrow F' = 3/F = 2 \rightarrow F' = 2$ crossover line, and the $F = 2 \rightarrow F' = 3/F = 2 \rightarrow F' = 1$ crossover line of ^{87}Rb. The locations of the corresponding peaks in the two spectra agree well, placing a limit on the possible systematic frequency offset between the two spectra of (0.08 ± 0.78) MHz. We note that the RF drive frequency of the AOM for this measurement was 200 MHz; a laser frequency difference of this magnitude (or twice this magnitude) would show up as a very substantial frequency shift between the two saturated-absorption spectra.

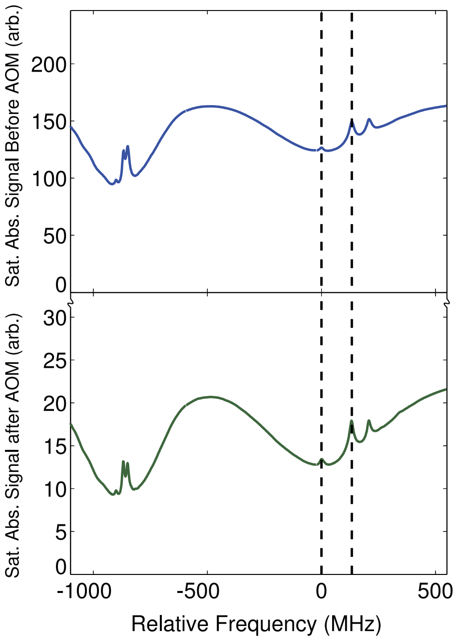

FIG. 3. Comparison of saturated absorption spectra on the rubidium cycling transition. The top panel shows a spectrum taken by scanning the frequency of the laser beam entering the acousto-optic modulator, while the bottom panel shows a similar spectrum taken simultaneously using light exiting the acousto-optic modulator. The absence of a frequency shift is illustrated by the occurrence of the saturated-absorption lines (marked by dotted vertical lines) at the same point in the laser scan before and after the modulator to within 1 MHz, as described in the text.

Although we have only set an upper bound on the magnitude of the frequency shift, we believe on theoretical grounds that the shift is potentially much smaller, as the RF drive frequency has essentially no fluctuations on the relevant time scales, i.e., the optical transit time (around 2 ns)and the time required by the sound wave to travel from the location of the first-pass beam to that of the second-pass beam if these are slightly misaligned (on the order of 20 ns or less).

If the extinction of the polarizer employed to block the zeroth order beam is imperfect, then the (0,0) leakage beam and the desired (+1, −1) beam will interfere at the output, and any time-varying differential phase shift between these two beams will result in amplitude and phase/frequency noise of the combined beam. Because these two beams traverse the same path in opposite directions, however, low frequency (less than ∼1 kHz) vibrations will result in common-mode phase rather than differential phase shifts for the two directions. Thus such output noise is doubly suppressed, both by the extinction ratio of the in-line polarizer and by the common-mode rejection of noise at low frequency, where the acoustic noise spectral is typically highest.

We have measured an extinction ratio of 40 000 (30 nW out of 1.22 mW, or around 46 dB) for this shutter, using a linear film polarizer (Thorlabs LPNIR050, with nominal extinction ratio of 173 000 at 780 nm) in the double-pass region and an identical polarizer at the shutter output to remove an undesired reflection from the AOM crystal. A low-extinction polarizer at the shutter input was also employed, and a light shield was used in the vicinity of the detector to absorb stray light from the various components of the shutter. Further improvements, approaching the rated polarizer extinction ratio, could most likely be achieved by enclosing the shutter in a light-tight enclosure or even anti-reflection-coating the AOM. However, if very high extinction is needed, a more robust approach suitable for many applications would be to combine the high-speed acousto-optic shutter with a slower mechanical shutter to block any residual light completely.

The double-pass efficiency of this setup has been measured to be 45% in configuration (c) of Fig. 2. This is approximately the expected optimal double-pass efficiency for the AOM employed, which has a rated single-pass efficiency of

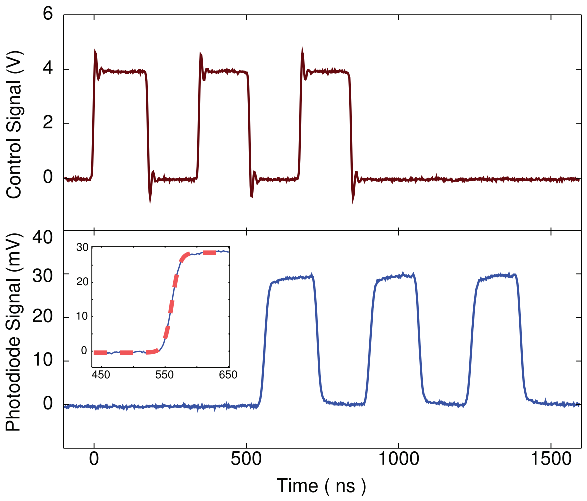

FIG. 4. Illustration of switching speed of shutter. A burst of three light pulses at a frequency of 3 MHz was generated by the acousto-optical shutter and collected on a photodiode. The manufacturer-specified response time (10%–90% rise time) of the photodiode under the experimental conditions is 2 ns. The inset shows the results of a sigmoidal fit (dashed red line) to a single-pulse rising edge (solid blue line); the fit yields a time constant of 6.1 ns, or a 10%–90% rise time of 26.8 ns. This value is close to the expected 25 ns transit time of the acoustic wave across the ∼100 μm beam waist. The reproducible delay between control and output pulses is due to the control electronics, and not intrinsic to the method.

70%. By using a higher-efficiency AOM, double-pass diffraction efficiencies of 80%–90% should be achievable, as in a conventional double-pass AOM configuration.[13] The present method differs from the conventional double-pass configuration because of a slight asymmetry between light diffracted into the +1 and −1 orders, due to the fact that the acoustic wave direction breaks the plus/minus symmetry. However, as shown in the analysis section below, this asymmetry is very small for the present application, and should have no significant effect on diffraction efficiency.

Results of a characterization of the switching speed are shown in Fig. 4. A burst of several light pulses was generated by the acousto-optical shutter and collected on a photodiode with a manufacturer-specified rise-time of 2 ns. A fit of the photodiode signal yielded a time constant of 6.1 ns, or a 10%–90% rise time of 26.8 ns, close to the expected ∼25 ns transit time of the acoustic wave across the laser beam waist. This rise time could be improved by tighter focusing of the in-going laser beam.

V. ANALYSIS

To first approximation, the Bragg angle depends only on the crystal acoustic wavelength, so that the up-shifting and down-shifting Bragg scattering events occur symmetrically about the planar wave-fronts of the acoustic wave. The motion of the acoustic wave, however, induces a small asymmetry between the incoming and outgoing angle, as measured from the instantaneous Bragg planes in the crystal. One can think about this asymmetry as arising from the motion of the acoustic wave during the time the light takes to traverse the crystal, which effectively tilts the Bragg planes by a small angle on the order of v_s/c, where v_s is the sound speed in the crystal and c is the speed of light in vacuum. The scattering asymmetry can be analyzed more precisely by transforming from the laboratory frame to the rest frame of the acoustic wave. We consider that in the laboratory frame the sound travels in the positive y direction with speed v_s and angular wave number k_s, and the incident laser beam has angular frequency ω. If we transform to a reference frame co-moving with the acoustic wave, the pattern of alternating regions of compression and rarefaction will be stationary, with wave number $k_s' = k_s/\gamma$, where $\gamma = (1 - \beta^2)^{-1/2}$ and $\beta = v_s/c$. In this transformed frame, the light undergoes ordinary Bragg scattering from the stationary density modulation, so that we can write the incident wave vector as $-k_y'\hat{\mathbf{y}} + k_x'\hat{\mathbf{x}}$ and the outgoing wave vector as $k_y'\hat{\mathbf{y}} + k_x'\hat{\mathbf{x}}$. The Bragg condition further implies that $2k_y' = k_s'$. (Although the x components of each wave vector are modified by refraction, the y components are the same inside and outside the crystal.) Denoting the optical frequency in this frame as ω', we can then transform back to the laboratory frame to find the following quantities:

$$
\begin{aligned}
\omega_{\rm in} &= \omega'\gamma - \beta c k_s/2, \\
\omega_{\rm out} &= \omega'\gamma + \beta c k_s/2, \\
k_{\rm in,y} &= -k_s/2 + \gamma\beta\omega'/c, \\
k_{\rm out,y} &= k_s/2 + \gamma\beta\omega'/c,
\end{aligned}
$$

where the subscripts in and out indicate the unscattered and scattered light, respectively, primed quantities are measured in the acoustic rest frame, and unprimed quantities are measured in the laboratory frame. Eliminating ω', we can write

$$
\begin{aligned}
k_{\rm in,y} &= -\frac{k_s}{2\gamma^2} + \frac{\beta\omega_{\rm in}}{c}, \\
k_{\rm out,y} &= \frac{k_s}{2\gamma^2} + \frac{\beta\omega_{\rm out}}{c}.
\end{aligned}
$$

The angles of the two beams in the laboratory frame can then be computed as $\theta_{\rm in} = \sin^{-1}(-k_{\rm in,\,y}/k_{\rm in})$ and $\theta_{\rm out} = \sin^{-1}(k_{\rm out,\,y}/k_{\rm out})$, where $k_{\rm in}$ and $k_{\rm out}$ are the angular wave numbers given by $\omega_{\rm in} = ck_{\rm in}$ and $\omega_{\rm out} = ck_{\rm out}$. Explicitly,

$$
\begin{aligned}
\theta_{\rm in} &= \sin^{-1}\left(\frac{k_s}{2\gamma^2 k_{\rm in}} - \beta\right), \\
\theta_{\rm out} &= \sin^{-1}\left(\frac{k_s}{2\gamma^2 k_{\rm out}} + \beta\right).
\end{aligned}
$$

The leading-order modification of the scattering angles is, as indicated earlier, equivalent to a rotation of the scattering planes by an angle β. Note, however, that for Bragg diffraction in the opposite sense (e.g., down-shifting instead of up-shifting), the rotation angle is also opposite. Thus, in a double-pass configuration, in which the first pass involves a positive frequency shift and the second pass a negative frequency shift, the first-pass diffracted beam and the second-pass incident beam are both rotated away from the symmetry axis, and by equal angles β, maintaining the symmetry of the setup in Fig. 2. It is worth noting that for a typical acousto-optic material, $v_s \approx 4 \times 10^3$ m/s, yielding $\beta \approx 1.3 \times 10^{-5}$, or a rotation angle of 13 μrad. For comparison, a diffraction-limited gaussian beam of waist 1 mm, has a spread in angle of around 500 μrad. Hence, even for a relatively large laser beam, this effective rotation of the Bragg planes causes only a minor change in the axial position of the double-pass lens in Fig. 2.

VI. CONCLUSIONS

We have demonstrated a method for switching or amplitude-modulating a laser beam via the acousto-optical effect, without the usual accompanying frequency shift. This method allows stabilization of the laser frequency at the shutter output frequency, which is useful in atomic physics experiments where the frequency reference and science sample are often the same atomic species. Because the output is independent of the RF frequency employed, the method allows the acousto-optic modulator to be driven at the RF frequency of peak efficiency. This technique is also well suited for chopping and for rapid arbitrary amplitude modulation of a laser beam. In the present work, we have demonstrated the lack of frequency shift with sub-megahertz uncertainty, and have shown switching times around 25 ns. The shutter efficiency is similar to that of a conventional double-pass acousto-optic modulator. The resulting system is expected to find applications in a variety of atomic and optical physics experiments.

ACKNOWLEDGMENTS

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