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Master Thesis in Physics
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handed in on

October 16, 2020

Spin Selective Imaging of Ground State Potassium Atoms

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Physics Institute in **Munich**

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Spin Selective Imaging of Ground State Potassium Atoms

Robin Eberhard

Abstract

Abstract

Zusammenfassung

Abstract

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Coherent light produced by lasers is the key ingredient in ultracold atom experiments in order to work with the atoms on a quantum level. This allows, amongst other things, to drive interactions between the atoms or select specific spin states out of the system. It is important to have control over the full parameter space of the electromagnetic waves interacting with the atoms, which is where light modulators serve as a powerful tool. Light passing through such an optical component will have its frequency, amplitude or phase changed, based on inputs that can be placed onto the modulators.

Two important components are highlighted in the following, these are electro-optical modulators (EOMs) and acousto-optical modulators (AOMs). Some preliminary theory is discussed, which is followed by experimental evaluations and implementations.

3.1 Theory on Polarization

Amongst frequency and amplitude, there is another parameter that can generally be affected in monochromatic electromagnetic waves, which is the polarization. It is the orientation of the wave in space, transverse to the direction of movement. In general, a wave travelling along the z-axis can be oriented somewhere in the x-y plane. Therefore, writing the electric field component of the light in this basis takes the following form:

Reviewers: I only discuss transverse polarization, should I keep it this way or do I make a comment about longitudinal polarization?

$$\mathbf{E}(\mathbf{x}, t) = E_x cos\left(kx - wt + \phi_x\right) \mathbf{e_x} + E_y cos\left(ky - wt + \phi_y\right) \mathbf{e_y}. \tag{3.1}$$

Here, k and w refer to the wave number and frequency respectively. Depending on the amplitudes E_x and E_y and the phases ϕ_x and ϕ_y, the wave can be in different polarization states. If it is not possible to write the wave in this basis, the light is unpolarized. Otherwise, it is **linear**, when either one of the amplitudes E_x or E_y is zero or when the phase difference $\Delta\phi = \phi_x - \phi_y$ evaluates to 0 or π. It is **circular**, when the phase difference $\Delta\phi = \pm\pi/2$

and the amplitudes are the same, $E_x = E_y$. In any other case, the wave is **elliptically** polarized.

From this point, we can see how to create a device that modifies the polarization. We can do this by retarding one axis stronger than another. Given a material with two refractive indices n_x and n_y along the axes x and y, we then get the phase shifts:

$$\phi_x(z) = k_0 n_x z \tag{3.2}$$

$$\phi_y(z) = k_0 n_y z \tag{3.3}$$

where k_0 is the free space wave vector of the light. Then a device that retards the phase difference $\Delta\phi$ by $\pi/2$, which is a quarter of the wavelength, can change linearly polarized light to circularly polarized light (or vice-versa) and is therefore called a $\lambda/4$ waveplate. Similarly, if the phase difference is changed by $\Delta\phi = \pi$, or a half wavelength, then we can turn linear polarization around a given axis or change the orientation of circularly polarized light. This is then called a $\lambda/2$ waveplate.

3.2 Electro-optical modulators

ref fundamentals of photonics somewhere

Light travelling through a material generally has a speed smaller than the speed of light. This property of the material is the refractive index and is the ratio of the speed of light in the material to the speed of light in vacuum . Materials can change their refractive index by being exposed to an electric field, which in EOMs is generally a crystal connected to two electrodes. There are two prominent electro-optical effects that need to be distinguished. If the refractive index changes linearly with the electric field, the effect is called Pockels effect and the EOM is called a pockels cell. However if it changes with the square of the electric field, the effect is called Kerr effect. For this thesis, two Pockels cells were studied and therefore we will only discuss the pockels effect.

Reviewers: Philip proposed to mention the dispersion relation, but I'm not sure if it's relevant and how to work it in

3.2.1 Pockels effect

Following the argumentation from the book Fundamentals of Photonics , the pockels effect can be found by evaluating the refractive index with respect to the electric field applied to

ref

the modulator. Writing this as $n(E)$ and applying a taylor expansion, we get the following expression:

$$n(E) = n_0 + \frac{dn}{dE}E + \mathcal{O}(E^2) \tag{3.4}$$

The pockels effect is the linear dependence of the refractive index to the electric field, therefore higher orders are neglected. The prefactor can also be found by the change of electric impermeability $\Delta\eta$, which is the ability of a material to be penetrated by an electromagnetic field. From

$$\eta = \frac{1}{n_0^2}, \tag{3.5}$$

we get

$$\Delta\eta = \frac{d\eta}{dn_0}\Delta n = -\frac{2}{n_0^3}\frac{dn}{dE}E = \mathfrak{r}E. \tag{3.6}$$

To the reviewers: the book does the derivation using the electric impermeability, but maybe it makes sense to drop the pockels coefficient, because it's not needed in my case and write everything using dn/dE and then I don't need to write about the impermeability at all?

This results in the quantity $\mathfrak{r} = -\frac{2}{n_0^3}\frac{dn}{dE}$, which is called the Pockels coefficient given in units of $\mathrm{m\,V^{-1}}$. It can be measured by evaluating the refractive index of the material:

$$n(E) = n_0 - \frac{1}{2}\mathfrak{r}n_0^3E. \tag{3.7}$$

The pockels cells in this application act as dynamic wave retarders, therefore with the results from section 3.1, we can tune the phase difference $\Delta\phi = \phi_x - \phi_y$ along the axes x and y by applying an electric field.

We can see the effect on the phase difference by combining 3.1 and 3.2.1:

$$\begin{aligned}
\phi &= k_0Ln && (3.8)\\
&= k_0Ln_0 - \frac{k_0}{2}L\mathfrak{r}n_0^3E && (3.9)\\
&= \phi_0 - \frac{k_0}{2}L\mathfrak{r}n_0^3E && (3.10)\\
&= \phi_0 - \frac{\pi}{\lambda_0}L\mathfrak{r}n_0^3E && (3.11)
\end{aligned}$$

where the relation $k_0 = 2\pi/\lambda_0$ of the wave number was used.

It is now instructive to calculate the phase difference, which gives information about the change in polarization. The relations for the refractive indices in the two axis basis are labeled as:

$$n_x(E) = n_{0,x} - \frac{1}{2}\mathfrak{r}_x n_{0,x}^3 E \tag{3.12}$$
$$n_y(E) = n_{0,y} - \frac{1}{2}\mathfrak{r}_y n_{0,y}^3 E \tag{3.13}$$

and then the phase difference becomes:

$$\Delta\phi = \phi_{0,x} - \phi_{0,y} - \frac{\pi}{\lambda_0} EL\left(\mathfrak{r}_x n_x^3 - \mathfrak{r}_y n_y^3\right) \tag{3.14}$$
$$\Delta\phi = \Delta\phi_0 - \frac{\pi}{\lambda_0} EL\left(\mathfrak{r}_x n_x^3 - \mathfrak{r}_y n_y^3\right). \tag{3.15}$$

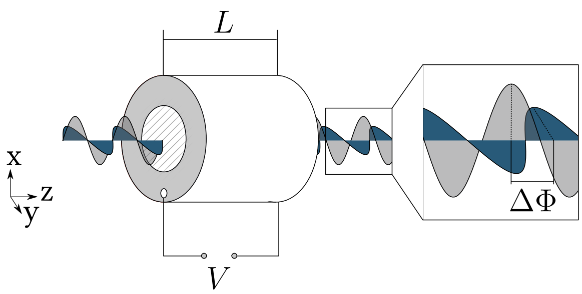

Figure 3.1: Schematic view of light passing through an EOM of length L. The electrodes are positioned on the front and back side of the modulator, the same faces the light enters and exits. The light exiting the EOM has a relative phase shift $\Delta\Phi$ depending on the change of refractive index due to the applied voltage V.

The electric field is generated by applying a voltage V to two electrodes that are separated by a distance d and therefore $E = V/d$. We can then define a half-wave voltage V_π:

$$V_\pi = \frac{d}{L}\frac{\lambda_0}{\mathfrak{r}_x n_x^3 - \mathfrak{r}_y n_y^3}. \tag{3.16}$$

Thus, the phase difference can be rewritten as:

$$\Delta\phi = \Delta\phi_0 - \pi\frac{V}{V_\pi}. \tag{3.17}$$

With this it is clear, that applying the voltage V_π, the pockels cell will act as a lambda-half waveplate. A visual represantation of the modulator and the light passing through it is given in Figure 3.1.

3.2.2 Driving a pockels cell

Rise and fall times of pockels cells can go as low as nanoseconds. To make use of this speed, one has to deploy clever ways to drive the voltages, especially when these potentials are in the kilovolt-regime. For the two Pockels cells discussed in this thesis, specialized drivers by BME-Bergmann were used. ref

Schematically, the driver is divided into four inputs that are controlled from the user: ON A, ON B, OFF A and OFF B. These inputs control switches on either side of the pockels cell, so A controls one electrode and B the other. Most importantly, the ON X and OFF X (X referring to either A or B) switches work exclusively, so sending a high to ON X will also send a low to OFF X and vice-versa. It is then possible to apply either a positive high voltage or a negative high voltage, depending on the state of the switches. For full identification of the circuit, which is given in Figure 3.2, the side containing the positive voltage information is called high side and similarly the side containing the negative voltage information is called low side.

A requirement for our experiment is to have the EOMs work consistently. This means it is preferrable to only apply one type of voltage, because it can not be guaranteed that applying the same voltage with different polarity results in the same shift polarization. Most notably, the linearly polarized light has to be perfectly aligned on the axis of the EOM to rotate it 90° in either direction. This is in general unrealistic, not only due to human error, but also because the polarization may drift with time.

This means, only positive voltages will be applied, which results in the timing diagrams in Figure 3.3.

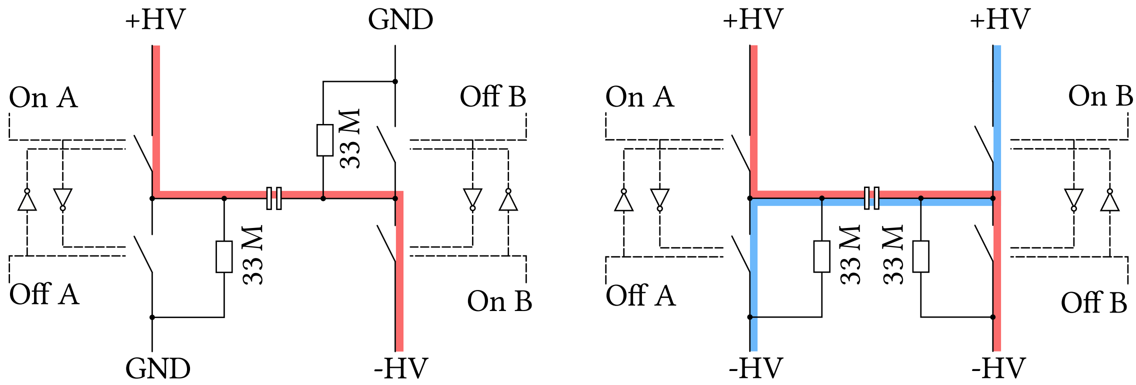

Figure 3.2: Schematic of the high voltage switches used inside the bpp-type (left) and dpp-type (right) pockels cell driver from BME Bergmann. Not-Gates on both A and B sides ensure that there is always a potential over the pockels cell. The blue and red paths indicate the connection to apply a positive and negative voltage over the pockels cell respectively.

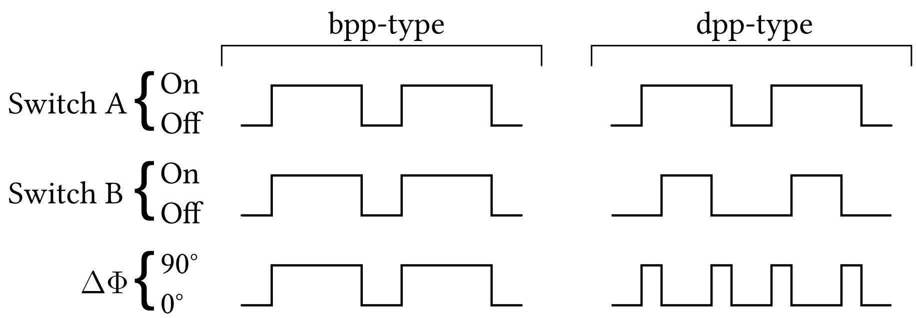

Figure 3.3: Timing diagrams for the pockels cell drivers to turn the polarization of the EOM 90°. To get a positive high voltage from the bpp-type driver, the A and B side ON/OFF switches are flipped simultaneously. The dpp-type driver is more flexible, since it also allows negative voltages. The timings displayed here are an example to only apply positive voltages across the pockels cell.

3.2.3 Evaluation of Leysop Pockels cells

schematic

The following pockels cells from Leysop Ltd. where chosen with the application in mind of switching light on the nanoseond scale on and off. Pockels cells can fulfill this requirement by exploiting the fact that linearly polarized light can be filtered out. This is best achieved by placing a polarizing beam splitter directly after the modulator. This way, the setup can be configured such that applying no voltage means light passes through the beam splitter, while applying V_π means the light gets reflected 90° off the beam splitter. Two pockels cells were characterized by placing a photodiode on either end of the beam splitter. The EOMs are labeled by the material of their nonlinear crystal, rubidium tanyl phosphate (RTP) and β-bariumborate (BBO). Their characteristics are summarized in table 3.2.3.

	RTP	BBO
Aperture (crystal dimensions)	3 mm	3 mm
Total crystal length (2 crystals)	30 mm	50 mm
Approximate half wave voltage (1064nm)	1.0 kV	2.8 kV
Peak damage threshold (1064nm, 1ns pulse)	$> 1\,\mathrm{GW\,cm^{-2}}$	$> 1\,\mathrm{GW\,cm^{-2}}$
Insertion loss	$< 2\,\%$	$< 1.5\,\%$

Table 3.1: Characteristics of the two pockels cells with their respective non-linear crystal materials being RTP and BBO. The aperture, damage threshold and insertion loss are given for future reference.

Example traces for the RTP and BBO are given in Figure 3.2.3. The peak at the start of the switch is an artifact of the photodiode. Moreover, the rise and fall times could not be resolved due to the limitations of the photodiode, a home-built model with a bandwidth of roughly 22 MHz.

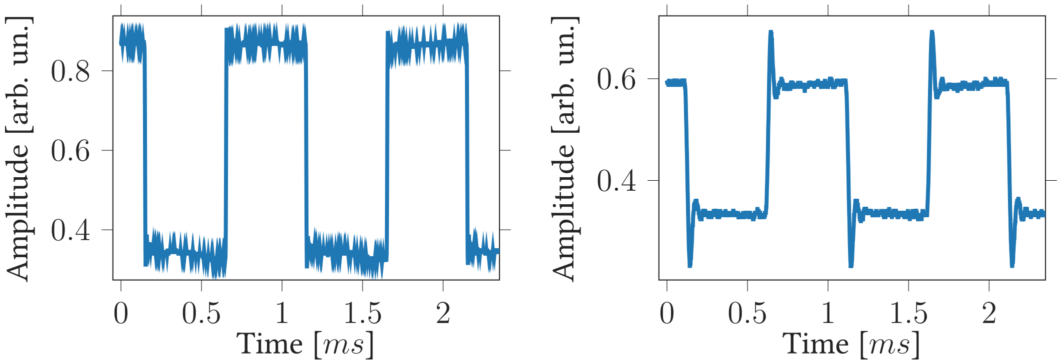

Figure 3.4: Example traces of light passing through an EOM and filtered using a polarizing beam splitter. The materials used are RTP (left) and BBO (right). The absolute value of the amplitude depends on the input power of the laser and was different for both measurements.

Stress on the crystal causes the amplitude of the laser on the output of the EOM to be inconsistent when driving the pockels cell for long times (~1 s) and high repetition rates (~MHz). This effect can be reduced by alternating the voltage applied to the crystal, which results in Figure 3.2.3, however the effect can only be seen on the RTP crystal and not on the BBO. With this information, it is clear that the RTP crystal should be driven with frequencies up to 1.2 MHz or in the range 1.5 to 1.7 MHz. The amplitude was extracted from the traces by fitting a fourier series.

In order to measure the extinction ratio, the repetition rate is set to 100 kHz, where the amplitude is consistent. Measuring first the dark current of the photodiode and then taking

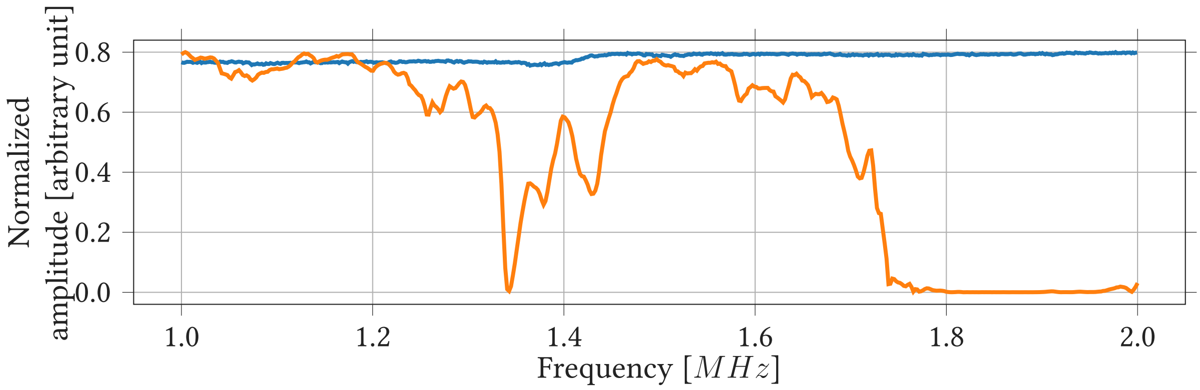

Figure 3.5: Shown is the amplitude of a laser whose polarization was rotated by a pockels cell and then filtered using a polarizing beam splitter. The frequency is the repetition rate of the voltage placed into the EOM. The two materials are RTP (orange) BBO (blue). The curves are normalized to their maximum value.

the signal on the output of the beam splitter results in the extinction ratio found in Figure 3.2.3.

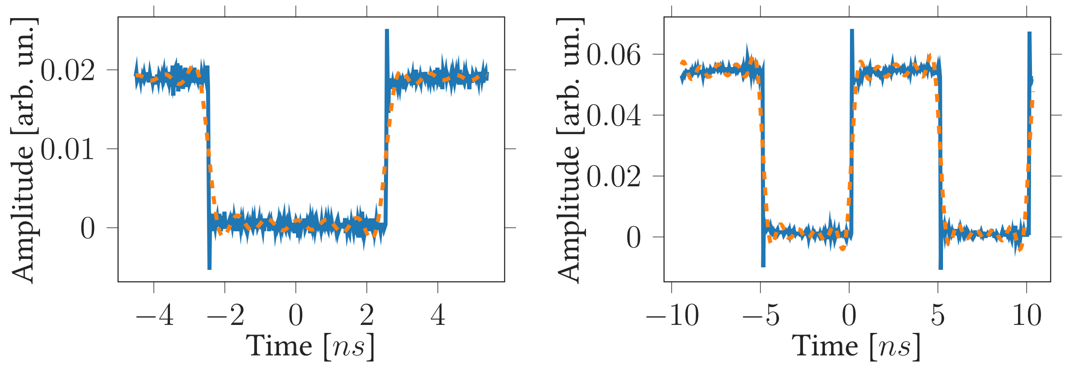

Figure 3.6: Measurements of extinction ratio for RTP (left) and BBO (right). The dashed lines indicate the fourier series fit in order to find the high and low level of the signal. The results are $> 108 : 1$ for RTP and $> 129 : 1$ for BBO.

BBO

3.3 Acousto-optical modulators

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Statement of Authorship

I herewith declare that this thesis was solely composed by myself and that it constitutes my own work unless otherwise acknowledged in the text. I confirm that any quotes, arguments or concepts developed by another author and all sources of information are referenced throughout the thesis. This work has not been accepted in any previous application for a degree.

Munich, October 16, 2020

Signature