High-Speed Integrated Electro-Optic Modulation and Up-Conversion for Cold Atom Experiment in the Visible Range (**HEIDI**)

Executive Summary Report (ESR)

Prepared by

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Cold atom experiments currently use bulky and heavy table-top laser sources, frequency converters and bulk modulators used to modulate the laser light on-off state with MHz speeds. All these different devices are used in conjunction to prepare and control atoms for fundamental quantum science and quantum information experiments, and usually take up the space of a small room. Our goal is to miniaturise and integrate these components on a small optical chip, which not only allows to perform the experiments using less space, but also allows them to be performed while using less energy to drive the individual components with a much more stable and precise operation due to the benefits of integration.

This project aims to, in a first step, integrate the modulator used to manipulate the atoms in the trap by on- and off-keying of an optical signal in the range of 760 nm to 800 nm with speeds reaching several GHz. However, to have efficient and good control over the atom, the on- and off-state of the modulated signal need to be very precise and distinguishable, which is defined by the extinction ratio of the modulation (i.e. the power ratio between the on- and off-state of the signal). On top of that, the off-state has to have very low remaining power to have full control over the trapped atom. To achieve these requirements, i.e. the fast modulation and the clean on- and off-state and high extinction ratio, we use the emerging thin-film lithium niobate on insulator platform. Lithium niobate is a well-known material in the telecommunication industry and is already used since several decades to encode and transmit data over long distances. However, those devices are very large since a bulk crystal of lithium niobate has to be used. Since 2014, the thin-film lithium niobate technology is available, which allows us to miniaturise the optical circuits and to guide the light to a cross section of about one square micrometre and increase efficiency and reliability of these new devices significantly. What makes this material so special is its birefringence and non-centrosymmetry. The former means, that of the three available crystal axes, two have identical properties and one slightly differs (called the crystal c-axis). The latter is what leads to the materials strong second order non-linearity, which we can use to manipulate a signal in different ways ranging from modulation to wavelength conversion.

Thin-film lithium niobate, due to the inherent properties of the material and achievable small sizes of structures guiding the optical signal, allows us to reach modulation speeds of tens of GHz using the electro-optic effect with a low driving voltage of below 10 V and comparatively low engineering effort. As the modulator, a 7.3 mm long Mach-Zehnder interferometer is used, where the input signal is split evenly into two arms at the beginning of the device. To make use of the electro-optic effect, an electrical RF signal is then applied to one of the arms to periodically change the phase of the optical signal, which leads to destructive (off-state) and constructive (on-state) interference of the signal at the output of the modulator. The power consumption and efficiency of the modulator is then directly related to how well the RF and optical signal interact (impedance matching) and can be adapted or improved by engineering the geometry of the RF electrodes and optical layer.

As mentioned already, an important property of lithium niobate is its second order non-linearity, which is not present in other commonly used materials for integrated photonics such as silicon or silicon nitride. We can engineer this non-linearity and use it to convert an input optical signal at a wavelength of 1560 nm to an output optical signal at a wavelength of 780 nm (e.g. half of the input wavelength). Because of this, we are able to make use of the already available knowledge and high grade equipment used in telecommunication data transfer, which operates at similar wavelength as our input signal. The same non-linearity also doubles the extinction ratio of the converted light, meaning that if we achieve 20 dB extinction in the 1560 nm signal, the generated 780 nm signal will show an extinction ratio of 40 dB. To give some values in percentages, if the difference between the on- and off-state is 20 dB, it means that the off-state is still at a level of 1 % of the power of the on-state. For an extinction ratio of 40 dB, this value reduces to 0.01 % and defines the low power off-state required for precise control over quantum experiments using trapped atoms. A sketch of the described system is shown in Figure 1 a), where the inset in b) shows an electron-scanning microscope image of the modulation part and c) shows a to-scale cross-section of the modulation area. The lithium niobate optical layer is shown in blue.

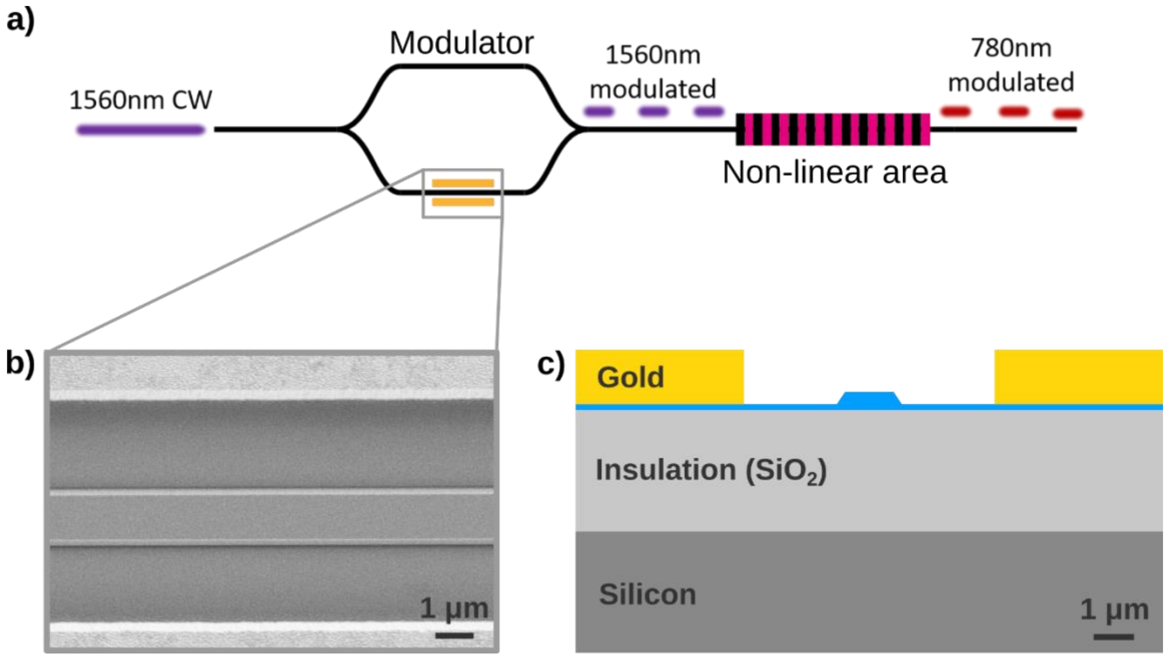

Figure 1. a) schematic of the full device with the modulator and non-linear area. The input signal at 1560 nm, the modulated signal at 1560 nm and the generated signal at 780 nm are given as well. b) Scanning-electron microscope image of the modulation area with the light guiding structure in the middle and the RF gold electrodes at the top and bottom of the picture. c) Cross-section of the modulation area in scale, showing the 2 µm thick insulation layer and the lithium niobate optical layer in blue.

In Figure 1 a), the non-linear area is depicted as a sequence of different coloured lines (black and purple). This depiction is close to reality as we design the device such that the optical guides are perpendicular to the strongest non-linearity in the material, the crystal c-axis. To engineer the non-linearity, we have to match the phases of the two contributing wavelengths (1560 nm and 780 nm) such that, during the conversion process, the energy transfer from one signal to the other can occur in an efficient way. This is, roughly speaking, similar to impedance matching used for the RF part of the system. Efficient energy transfer is achieved by periodically inverting (poling) the c-axis of the crystal at a periodicity defined by the geometry of the optical layer (i.e. width and depth of the light guiding structure), which in our case is 2.5 µm. To pole the crystal, we deposit one ground and one signal metal electrode in the shape of two facing combs, with the spacing of the comb teeth defined the periodicity needed, and the spacing between the two combs on the order of 15 µm. The application of several strong electric field pulses in the range of 21 V/µm to 41 V/µm then inverts the crystal locally, forming the non-linear area. This periodically poled lithium niobate area (or PPLN) can then be imaged and investigated to either improve the poling process or get an initial estimation of the expected non-linear conversion efficiency of the system. Of course, the longer this non-linear area is, i.e. the longer the optical signals are allowed to interact via the poled structure, the more light is converted from 1560 nm to 780 nm and thus output power increases. Here, we use an 8 mm long non-linear interaction area.

To couple the light to and from the chip, we employ diffractive grating couplers and commercially available optical fibres for the respective wavelengths. Grating couplers allow only the polarisation state they are designed for to enter the chip and therefore offer precise control over the polarisation and allow to align it with the crystal c-axis in a straightforward manner. This is important to operate the device at the designed parameters. Furthermore, they can be tailored to emit light at a certain angle and focus the beam at a certain position in space (e.g. at the position of a possible atom), from which could benefit later applications of this device. Their coupling losses can be improved from the current -4 dB for 1560 nm and -7 dB for 780 nm to values closer to -2 dB with moderate effort, allowing for future packaging of the full device for easy use in laboratories.

Here, we report the successful integration of the above-mentioned modulation scheme in our thin-film lithium niobate on insulator platform as a proof-of-concept device. Fabrication is done using electron beam lithography to initially define the lift-off mask for the poling metal electrodes, which are then deposited in an electron beam evaporation system. After the successful poling step, electron beam lithography is again used to define the mask of the optical layer. Inductively coupled plasma etching then engraves the optical layer into the thin-film and a third lithography step is used to define the RF electrodes again using an evaporation and lift-off process as for the poling electrodes.

The device operates at an input wavelength of 1536 nm with a modulation speed of up to 50 GHz and extinction ratio of 20 dB and 7 V driving voltage to switch between the on- and off-state of the signal. The non-linear signal generated at 768 nm in the non-linear section shows the same modulation behaviour, however with a doubled extinction ratio of 40 dB and an output power of 0.3 mW at an input power of 100 mW. We could fabricate a total of six devices on a 10 mm x 10 mm area corresponding to a small footprint per device of 10 mm x 1.3 mm. The main challenge during the development of the device is the engineering and optimisation of the non-linear area, as any deviation from the theoretical ideal operation point found in the design phase leads to a decrease in the non-linear conversion efficiency at the desired wavelength. Here, stabilisation and full understanding of the poling process is the key challenge, which can be overcome with careful investigation, iteration, and experience. Furthermore, the driving voltage of now 7 V can further be reduced to 5 V by properly engineering the insulation layer, which isolates the optical layer, where our signal is travelling, from the silicon handle layer (here, we used an insulation layer thickness of 2 µm). As RF signals are generally disturbed by silicon, increasing this layer thickness will lead to a lower driving voltage, although it will require a revisit of the impedance matching requirement for high modulation speeds.

Future application of these devices can not only be found in directly manipulating trapped atoms or ions for quantum physics experiments, but also in e.g. Rubidium atom clocks (see Figure 2), where our HEIDI modulator is used to precisely trigger a transition in the atom. The emitted light from this transition, which is very well defined in terms of both frequency and wavelength, can then in turn be used to stabilise a laser system.

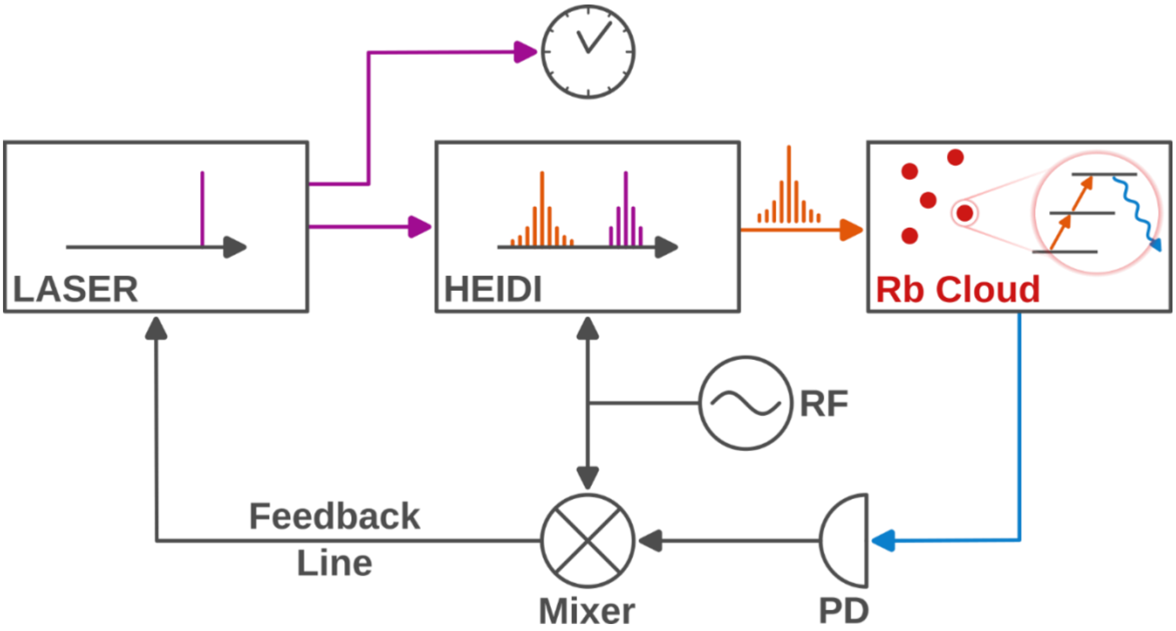

Figure 2. Laser stabilization using our presented HEIDI modulator to trigger a well defined transition in a Rubidium atom detected by a photo-detector (PD).

We can see here already, that while the integrated HEIDI optical circuit takes the role of modulating and sending signals to the Rubidium atoms, many of the remaining parts of the setup (e.g. photodiode) can be integrated on the same chip, leading to further miniaturisation and stabilisation of such systems.