Mach-Zehnder modulator for optical pulse generation and fluorescence lifetime measurement.

Bachelor's Thesis submitted

to

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Mach-Zehnder modulator for optical pulse generation and fluorescence lifetime measurement

Mach-Zehnder Modulator zur Erzeugung optischer Pulse und zur Messung der Fluoreszenzlebensdauer

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Abstract

Femtosecond pulsed laser sources are usually employed to measure processes on the nanosecond time scales, such as the fluorescence lifetime of organic molecules. As an alternative, this work presents a broadband low-cost and compact nanosecond pulsed source using a fibre-coupled Mach-Zehnder modulator (MZM) in combination with a continuous-wave laser.

First, an electronic setup was built to send electronic pulses to the MZM to generate optical pulses as close to the ideal as possible. In particular, while the ON-state of the generated optical pulses corresponds to a constant voltage applied to the MZM (namely V_π), the voltage corresponding to the offset (namely V_{bias}), changes over time due to charge displacement and thermal drifts. A so-called bias controller was therefore implemented to continuously adjust the output of the modulator.

This configuration was then used to determine the fluorescence lifetime of a single dibenzoterrylene molecule embedded in a nanocrystal of anthracene (DBT:Anth), a well-characterised organic single-photon source. The measured value $\tau_{exp} = (4.1 \pm 0.5)\,\text{ns}$ is consistent with the literature value of $(4.1 \pm 0.4)\,\text{ns}$ [1, 2]. Some optimizations are suggested to improve the measurement.

Table of content

1 Introduction

"An interferometer is an optical device which utilizes the effect of interference [3]". It typically splits an incoming beam along two paths and manipulates the light before combining them again. This can be used for a wide variety of applications, e.g. to measure distance, time or rotations. This work focuses on amplitude modulation to measure physical events on the nanosecond scale. Applying a voltage to a certain nonlinear crystal placed in one path changes the phase of the light going through. When the beam recombines, the phase difference leads to constructive or destructive interference. The linear case is described by the so-called Pockels effect. The simplest example is a Pockels cell, but this device needs voltage in the order of kV to change the phase accordingly [4]. A compact alternative is a Mach-Zehnder modulator (MZM) which operates on a waveguide and can work with much lower voltages. The MZM is based on the Mach-Zehnder interferometer that was independently developed by Ludwig Mach [5] and Ludwig Zehnder [6] at the end of the 19th century. Nowadays, it is widely used in telecommunication applications [7] because of its capability for high bandwidth digital modulation. It also plays an important role in theoretical physics as a device to demonstrate quantum effects like the delayed choice quantum eraser [8] or to test different interpretations of quantum mechanics [9]. In the context of this work, the MZM will serve as a low-cost pulse source to measure the fluorescence lifetime of a single dibenzoterrylene molecule embedded in an anthracene nanocrystal (DBT:Anth). This is an organic source of single photons and a promising candidate for applications in nanophotonics and quantum optics [10–12]. The fluorescence lifetime is an important parameter, as it quantifies the rate of the emitted photons, i.e. the brightness of the single-photon source.

2 Theoretical background

This chapter gives an overview of the physical principles behind the experiment performed in this thesis. The first section illustrates the working principle of a Mach-Zehnder modulator (MZM) for optical pulse generation.

Then follows a derivation of the fluorescence lifetime using the Einstein rate equation. The last part describes the method for the lifetime measurement.

2.1 Mach-Zehnder modulator

The pulse source implemented in this thesis is a continuous-wave (CW) laser modulated by a fibre-coupled MZM as the one shown in Figure 1. This device provides a wide range of operational wavelengths, pulse widths and repetition rates. It consists of a chip-based Mach-Zehnder interferometer (MZI) with a nonlinear lithium niobate ($LiNbO_3$) crystal in one arm and exploits the Pockels effect to modulate the output power.

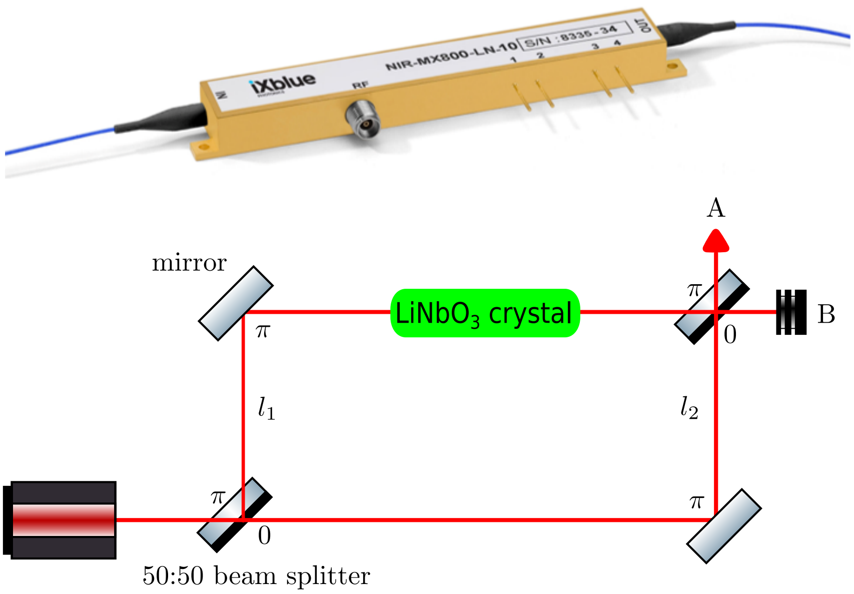


Figure 1: (top) Image of an iXblue MZM used in the setup. The model has a bandwidth of 10 GHz. This is a compact device with an edge lentgh of 10 cm which can be easily integrated into an existing optical setup. The picture is taken from [13]. (bottom) Schematic of a MZI. A light beam is split by a 50/50 beam splitter. The phase ϕ of the light in one arm is modulated by an electro-optical $LiNbO_3$ crystal. A second beam splitter recombines the beams and sends them towards path A out of the MZI or B where the light dissipates into the device. This allows to control the intensity at the output of the device.

2.1.1 Mach-Zehnder interferometer

A MZM can be interpreted as a MZI as the one sketched in Figure 1. The incoming light of wavelength λ is described by the electric field E_0 and the beam is split into two parts by the beam splitter, $E_2(t)$ along the top and E_1 along the bottom part. l_1 and l_2 are defined as the optical path lengths of the upper and lower path from source to output. In this case the difference in path length between the two arms is due to the $LiNbO_3$ crystal whose refractive index changes proportionally to the applied electric field. t is the optical path length of light passing through the beam splitter. Light can leave the modulator through output A while light going through output B dissipates into the device. Now the intensity at output A is calculated based on the derivation by Zetie [14]. The Fresnel equations [15, 16] for reflection and transmission of a wave at a dielectric medium imply that there is a phase change of π for a reflection when a wave propagating in a lower refractive index medium reflects from a higher-refractive index medium, but not in the opposite case [17]. This implies that light which is reflected from the backside of a beam splitter does not get phase shifted. Adding up all the phase changes along both paths amounts to the following phase difference at output A:

$$\begin{aligned} &2\pi + 2\pi\left(\frac{l_1 + 2t}{\lambda}\right) - \pi - 2\pi\left(\frac{l_2 + 2t}{\lambda}\right) \\ &= \pi + 2\pi\left(\frac{l_1 - l_2}{\lambda}\right) = \pi + \Delta\phi \end{aligned}$$

This definition of $\Delta\phi$ gives an output minimum for $\Delta\phi = 0$ at output A. The electric field E_A at output A is therefore the sum of the interfering beams [18] where ω is the angular frequency of the field.

$$E_A = E_1 + E_2 = \frac{1}{2}\mathrm{E}_0\left(\sin\left(\omega t\right) + \sin\left(\omega t - \Delta\phi\right)\right)$$

The output Intensity is proportional to the time average of E_A^2.

$$I_A = \frac{I_0}{2}\left[1 - \cos\left(\Delta\phi\right)\right] \tag{1}$$

For a phase difference of zero, no light leaves the MZI. This state is called OFF-state. For a phase difference of π, all light leaves the MZM. This is called the ON-state.

2.1.2 Linear electro-optic effect in non-linear crystals

To create optical pulses, the phase difference between the arm needs to be controlled. In an MZM this is done by exploiting the Pockels effect [19] which is a linear electro-optical effect that describes the change of the effective refractive index of a nonlinear optical material under the influence of an external electric field. When applying a voltage V, the refractive index n_3 changes proportionally, assuming linearly z-polarized light and an external electric field along the crystallographic z-direction.

$$\Delta n_3(t) = -\frac{1}{2}\mathrm{n}_3^3 r_{33} E_3(t) = -\frac{1}{2}\mathrm{n}_3^3 \mathrm{r}_{33} \frac{V(t)\Gamma}{\mathrm{g}}$$

The phase shift $\Delta\phi$ can be approximated as [20]:

$$\Delta\phi(t) = -\frac{2\pi \mathrm{L}}{\lambda}\Delta n_3(t)$$
$$\Delta\phi(t) = -\frac{\pi \mathrm{r}_{33}\mathrm{n}_3^3 \mathrm{L} V(t)\Gamma}{\lambda \mathrm{g}}$$

Where g is the gap between the electrodes around the waveguide and L is the length of the electrodes. The modulator is designed to use the biggest electro-optic coefficient $r_{33} = 33\,\mathrm{pm\,V^{-1}}$ [21].

An important parameter is V_π which corresponds to a phase shift of $\Delta\phi = 90°$ [18].

$$V_\pi = -\frac{\lambda g}{r_{33} n_3^3 L \Gamma} \tag{2}$$

This is the voltage that changes the output from destructive to constructive interference, where $\Gamma < 1$ is the efficiency of the inhomogeneous field by the electrodes. If we introduce an offset V_{bias} to the voltage and insert the expression for $\Delta\phi$ and V_π into equation (1) we arrive at

$$I_{\mathrm{out}}(t) = \frac{\mathrm{T_{mod}} I_{\mathrm{in}}}{2}\left[1 - \cos\left(\Delta\phi(t)\right)\right] = \frac{\mathrm{T_{mod}} I_{\mathrm{in}}}{2}\left[1 - \cos\left(-\frac{\pi n_{33}^3 r_{33} L}{\lambda \mathrm{g}}\left(V(t) - \mathrm{V_0}\right)\right)\right]$$
$$= \frac{\mathrm{T_{mod}} I_{\mathrm{in}}}{2}\left[1 - \cos\left(\pi \frac{V(t) - V_{\mathrm{bias}}}{V_\pi}\right)\right] \tag{3}$$

Where $I_{out} = I_A$, $I_{in} = I_0$ and T_{mod} is the optical transmission of the device. This was added to include the losses from the modulator. V_{bias} is bias voltage which attributes to the fact that the output of the MZM is not necessarily zero if no voltage is applied. This is caused by slight deviations in the lengths of the arms, thermal fluctuations and charge transport due to the applied electric field. Figure 2 shows the plot of equation (3). This is the so-called characteristic curve, which contains important information about the modulator. Measuring the half period gives the voltage V_π. The amplitude gives the extinction ratio, which defines the maximum dynamic between the OFF-state to the ON-state. The bias voltage V_{bias} can be deduced by the offset.

2.2 Fluorescence lifetime

The fluorescence lifetime τ is a measure of the average time a molecule spends in the excited state before returning to the ground state by emitting a photon [23]. The lifetimes of a fluorescent molecule can range from picoseconds to hundreds of nanoseconds [24].

An expression for τ can be derived from the Einstein rate equation [25] for the population of

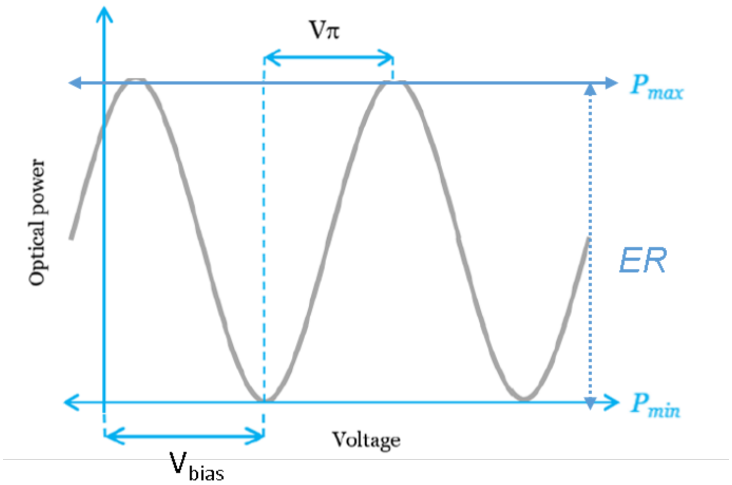


Figure 2: The characteristic curve defines many properties of an individual MZM. The curve is described by (3) if power instead of intensity is used. The amplitude gives the extinction ratio, which is defined as $ER(\mathrm{dB}) = P_{\mathrm{min}}(\mathrm{dB}) - P_{\mathrm{max}}(\mathrm{dB})$. The half period gives V_π which is the voltage required to switch the MZM from the off-state to the on-state. The bias voltage V_{bias} is the offset caused by unequal arm lengths, thermal fluctuations and charge transport compensating the applied voltage. This figure was modified from [22].

the excited state of a two-level system 3, which is a good approximation for the molecule studied in this thesis (see chapter 3.2.2). The Einstein rate equations can be used to describe the phenomena of population inversion, stimulated emission and lasing. This setup does not use an optical cavity, so stimulated emission is neglected. With only two energy levels, population inversion is impossible which leads to saturation of the fluorescence intensity. A full treatment can be found in [26]. At the beginning the molecule is in the ground state. Then it is excited by a laser pulse $u(t)$ to the excited state. The population of the ground state $n_1(t)$ and that of the excited state $n_2(t)$ depend on the relation between absorption rate A and spontaneous emission rate B of the molecule. A and B are the so-called Einstein coefficients. The dynamics of the excited population

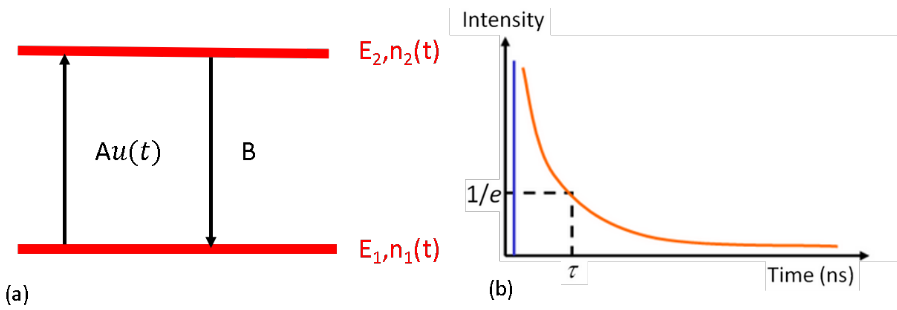


Figure 3: (a) Scheme of a two level system. E_i and $n_i(t)$ are the energy and the population of each state, respectively. $u(t)$ is the intensity of the incident radiation field of the laser pulse, A the absorption and B the spontaneous emission coefficient. (b) Decay curve taken from [27] derived from the Einstein rate equation, assuming a two level system. I_0 is the saturation intensity after the system gets pumped by a laser pulse which is the blue peak. Afterwards the system decays exponentially and $I(t = \tau) = \frac{1}{e} I_0$, where τ is the fluorescence lifetime.

can then be written as:

$$\frac{dn_2(t)}{dt} = \mathrm{A}u(t)n_1(t) - \mathrm{B}n_2(t)$$

When the pulse stops n_2 only depends on the spontaneous emission.

$$u = 0 \Rightarrow \frac{dn_2(t)}{dt} = -\mathrm{B}n_2(t) \tag{4}$$

With the boundary condition $\mathrm{N}_0 \coloneqq n_2(t=0)$ the solution of (4) is an exponential decay.

$$n_2(t) = \mathrm{N}_0 e^{-\mathrm{B}t} = \mathrm{N}_0 e^{\frac{-t}{\tau}} \tag{5}$$

Where $\tau = \frac{1}{\mathrm{B}}$. Therefore the fluorescence lifetime τ shown in Figure 3b is the time it takes for the population to go down by a factor of $\frac{1}{e}$. For the given setup with weak pumping, the intensity of the emitted light is proportional to the population of the excited state [27] and equation (5) can be written as

$$I(t) = \mathrm{I}_0 e^{\frac{-t}{\tau}}$$

I_0 is the saturation intensity after the system gets pumped by a laser pulse.

2.3 Time-correlated single-photon counting

To measure the fluorescence decay curve, a method which can resolve low levels of light with picosecond time resolution is needed. Time-Correlated Single Photon Counting (TCSPC) is an established statistical method that fulfils these criteria [28]. TCSPC is based on the detection of single photons of a periodic light signal, the measurement of the detection times and the reconstruction of the waveform from the individual time measurements [29, 30]. Each laser pulse starts the clock. The detection of a photon from the excited molecule stops the clock and the time difference is saved. The process is repeated millions of times from which a histogram is built, as shown in Figure 4. The data could then be fitted with an exponential decay according to equation (5) from which the lifetime τ can then be calculated.

Reverse TCSPC

Note that during each start-stop cycle only a single photon can be detected. After a stop signal, the detector is blind for a time, which is called dead time (see Figure 4). Moreover, in the case of single-molecule detection, the rate of detected fluorescence photons is very low. For high pulse repetition rates, it is more efficient to work in reverse mode, where the detection of a photon provides the start for the time measurement and an electrically delayed pulse from the laser

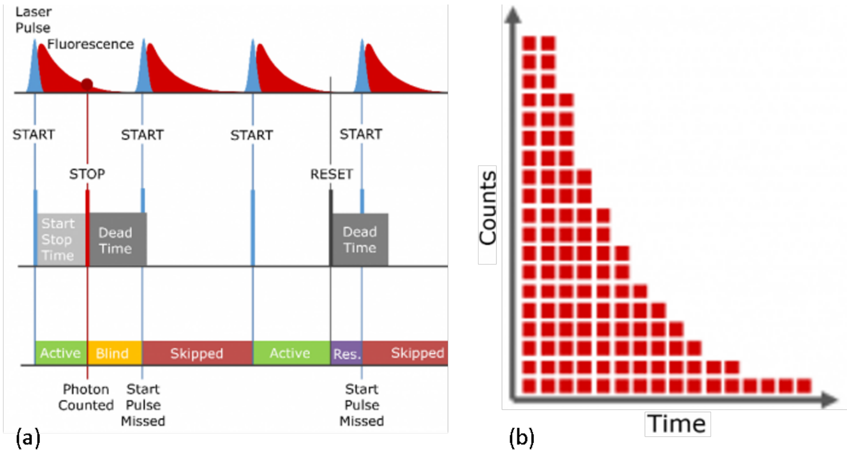


Figure 4: (a) TCSPC operation in forward mode with a low laser repetition rate (b) The measured number of counts for each time difference between start and stop signal gets saved. This is plotted in a histogram and fitted by an exponential decay to calculate the fluorescence lifetime. Figure modified from [31].

gives the stop, see Figure 4 for comparison. The advantage is that the clock only starts when a fluorescence photon arrives at the detector and unnecessary clock resets are avoided. The overall time that the electronics spend in dead time is reduced, since it only occurs after the detection of a photon [31].

3 Experimental setup

This chapter describes the electronic and optical experimental setups implemented during this thesis to drive a fibre-coupled Mach-Zehnder modulator (MZM, NIR-MX800-LN-10, iXblue) and to characterise the generated optical pulses. The obtained nanosecond-pulsed source was then used to measure the fluorescence decay time of a single molecule of dibenzoterrylene embedded in a nanocrystal of anthracene (DBT:Anth). For this, a laser wavelength of 764 nm is used which is outside the MZM operating wavelength range of 780 nm to 850 nm. To see the impact of working outside the suggested wavelength range the characteristics of the optical pulses are discussed in chapter 4 for two laser sources with different wavelengths, specifically @785 nm and @764 nm.

3.1 Electronic setup

In order to generate optical pulses from the MZM a fast pulse generator (PG, T240, Highland Technology) that delivers pulse amplitudes of up to 700 mV and with a width from 0.16 ns to 25 ns and a maximum repetition rate of 160 MHz was used. As presented in Figure 5 the PG is triggered by a waveform generator (WFG, DG400, Rigol) that can set the pulse repetition rate up to 125 MHz. Since the MZM typically requires input voltages of 3.5 V [13] to switch

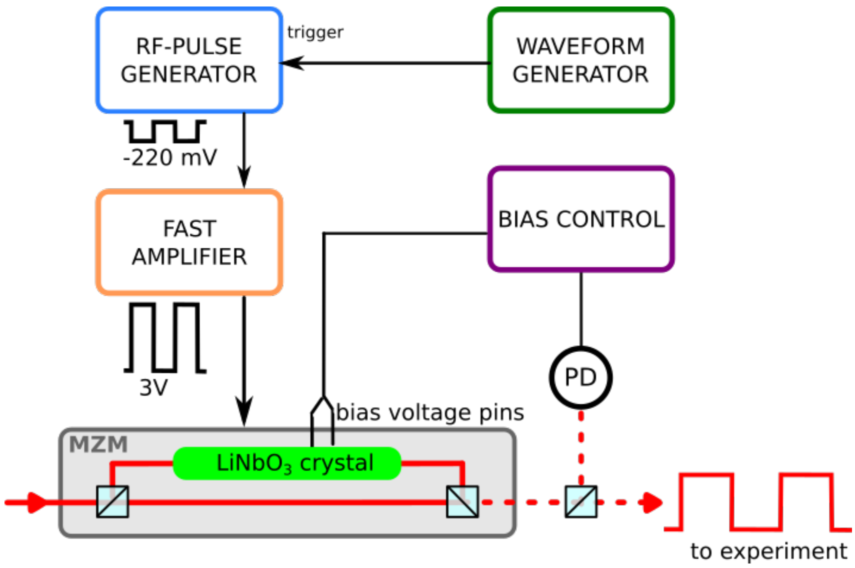


Figure 5: Schematic of the electronic setup implemented during this thesis. The output of the MZM is controlled by a fast RF-pulse generator (PG). The output from the PG goes through a fast amplifier to reach the necessary voltage to switch the MZM from the OFF-state to the ON-state. The trigger for the PG is provided by a WFG. The non-constant bias voltage V_{bias} is adjusted by a controller to ensure stable operation. This figure was modified from [27].

the output of the MZM from the OFF- to the ON-state, a voltage $V = V_\pi + V_{\text{bias}}$ needs to be applied. V_{bias} is usually $\neq 0$, since the two arms of the MZM can be different due to material inhomogeneity and manufacturing tolerances. Moreover, as will be discussed in Chap 4, several conditions can lead to a drift over time for the value for V_{bias}. For this reason, an automatic bias control circuit was set up using a Raspberry Pi 3b+ with a MCC 128 input (0 V to 5 V) and a MCC 152 output (0 V to 5 V, amplified −0.56 V to 5.3 V by a homemade amplifier) board (Figure 15a). The output voltage is sent to the bias input of the MZM and controlled with a python script shown in Appendix A.2 adapted from one developed in the group by Christian Liedl. The program starts sending a single voltage ramp between −0.56 V and 5.3 V in 0.2 s. The resulting optical power modulation at the MZM output corresponding to the characteristic curve (see Figure 2) is detected by a home-built photodiode whose responsivity curve is plotted in Figure 6. The output of the photodiode is then sent to the bias controller that fits the data with equation (3), as shown in Figure 15b. From here the value of V_{bias} is determined and sent back to the MZM as a DC value. This shows the linear regime of the PD, which is above the noise floor and below the saturation limit given by the load and the reverse voltage of the PD[32].

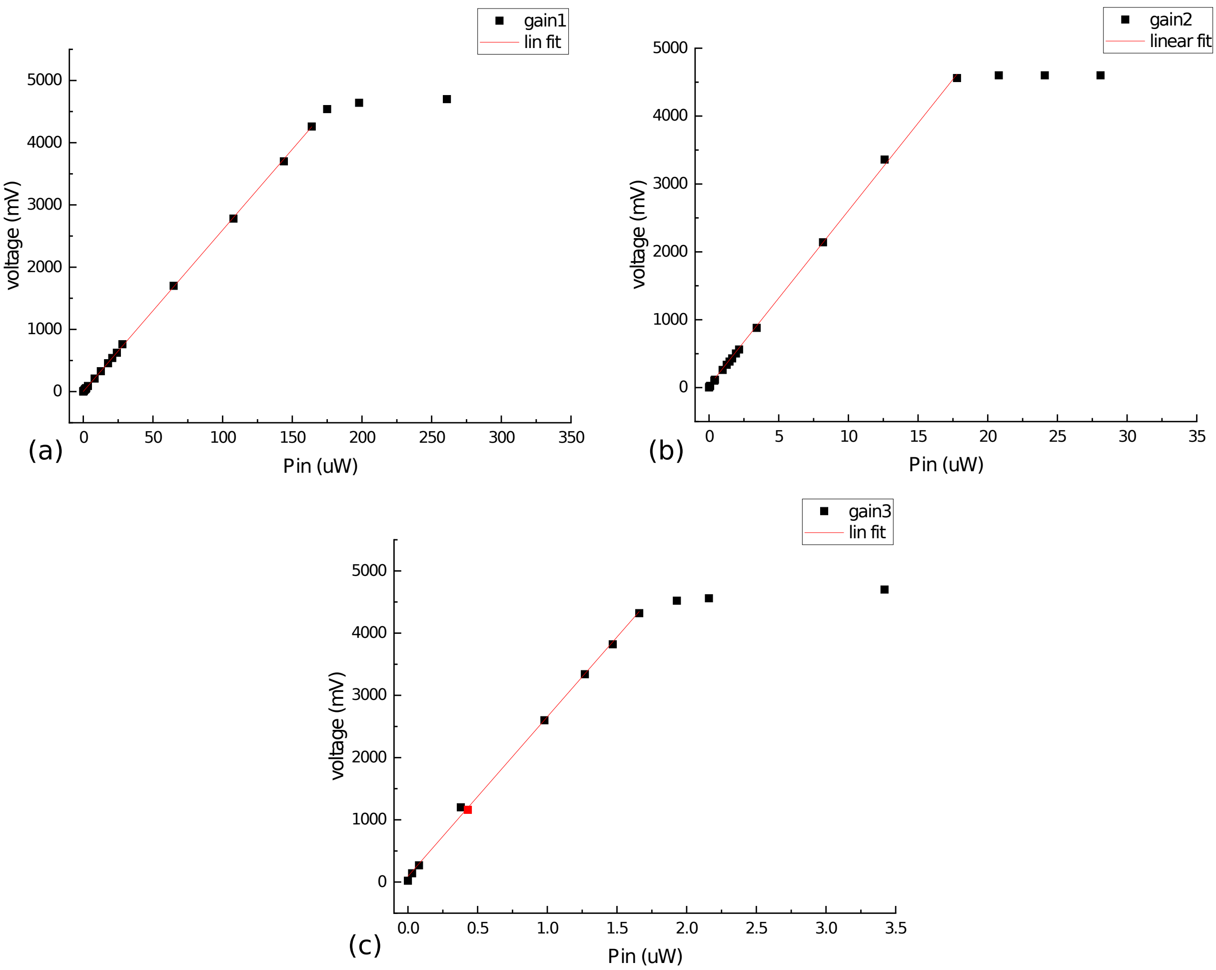


Figure 6: Characteristic curve for the homemade PD the three gains settings
gain 1: intercept (3 ± 3) mV slope: (25.93 ± 0.05) mV µW^{-1}
gain 2: intercept (29 ± 100) mV slope: (258 ± 8) mV µW^{-1}
gain 3: intercept (100 ± 60) mV slope: (256 ± 60) mV µW^{-1}

To adjust for the bias drift while using the MZM for an experiment (as in our case a fluorescence lifetime measurement), a portion of the optical output is sent to the photodiode by a half-wave plate (WPHSM05-785, Thorlabs) and a polarizing beam splitter (PBS122, Thorlabs). A summary of the used optical components can be found in Table 1.

abbrevation	Equipment	Model	Brand
ND	variable neutral-density filter	NDC-50C-4M	Thorlabs
SPCM	single photon counting module	AQRH-13-FC	PerkinElmer
LP	long pass filter	LPD02-785RU	Semrock
	objective	100x, oil, NA=1.4	Zeiss
mirror	broadband dielectric mirror	BB1-E03	Thorlabs
DM	dichroic mirror	FF776-Di01	Semrock
PBS	polarizing beam splitter cubes	PBS122	Thorlabs
	polarization maintaining fibre connector	ADAFCPM1	Thorlabs
	quarter-wave plate	WPQSM05-780	Thorlabs
	half-wave plate	WPHSM05-780	Thorlabs
iris	lever-actuated iris diaphragm	SM1D12	Thorlabs
PM fibre	polarization maintaining fibre	P3-780PM-FC-1	Thorlabs

Table 1: Overview of the optical equipment.

3.2 Optical setup

The electronic setup presented earlier is first integrated into an optical setup as sketched in Figure 7 to analyse the pulses of the MZM (NIR-MX800-LN10, iXblue) and afterwards a second optical setup presented in Figure 10 is used for the fluorescence lifetime measurement.

3.2.1 Pulse analysis

To test the performance of the MZM driven by the electronic setup described previously, we coupled it to a laser with a wavelength within its operating range [13]. A continuous-wave (CW) laser (DFB pro, Toptica, 785 nm) is used. An iris optimizes the collimated beam profile into a Gaussian spot to achieve higher incoupling efficiency shown in Figure 8. A polarizing beam splitter (PBS) in combination with a $\frac{\lambda}{2}$-plate splits part of the beam for the experiment. A variable neutral density filter (ND) is used to control the power sent into the MZM which should not exceed 10 mW [33]. The polarization of the free space beam is matched to that supported by a polarization maintaining (PM) fibre (P3-780PM-FC-1, Thorlabs), using a $\frac{\lambda}{4}$- and a $\frac{\lambda}{2}$- plate. The PM-fibre is chosen to match the specification of the MZM fibre which is connected with a low-loss fibre connector. The MZM output is monitored by a fast Photodiode (1024, New Focus) with 12 ps rise time and an oscilloscope (MSOS804A, Keysight) with 8 GHz bandwidth. The WFG controls the bias voltage. Details of the optical components with their respective abbreviations can be found in Table 1.

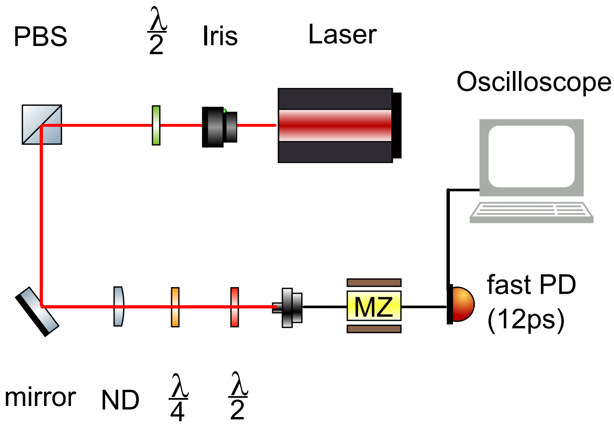


Figure 7: Scheme of the optical setup for aligning a free space laser into the fibre-coupled MZM. To analyse the pulses, the MZM output is monitored with a fast PD and an oscilloscope.

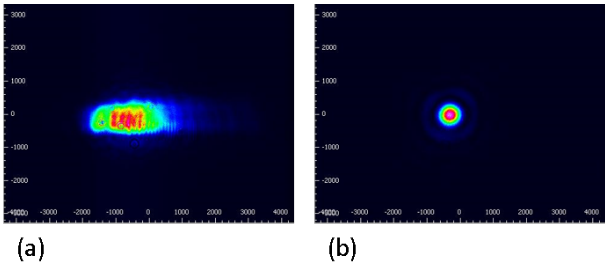


Figure 8: The Iris is used to optimize the beam shape into a Gaussian spot for an increased incoupling efficiency. Closing the iris results in a better shape, but loses laser power. (a) is the laser before the iris, (b) after the iris.

3.2.2 Fluorescence measurement

As an application, we used the MZM to perform a fluorescence lifetime measurement on a single molecule of DBT:Anth. This molecular system is a stable source of single photons in the near-infrared at room temperature [1, 34]. Its lifetime τ provides an estimation of the maximum rate of the emitted photons $\frac{1}{\tau}$.

Figure 9 shows the chemical structure and the simplified energy level scheme for DBT:Anth [2], highlighting the transition involved in the experiment. Specifically, we use a 764 nm-laser (yellow arrow) to excite the molecule into a vibrational level of the excited electronic state $|S_1\rangle$. From here, the molecule decays non-radiatively on a picosecond timescale into the vibrational ground state of $|S_1\rangle$. Finally, the molecular system relaxes to the electronic ground state $|S_0\rangle$ with the emission of a photon on a nanosecond timescale. This last transition is called fluorescence and occurs at longer wavelengths (lower energies) than the absorbed photon. This energy difference is called Stokes shift [23] and is exploited in our experiment for the measurement of fluorescence lifetime. For this, pulses generated by the MZM coupled to the 764 nm CW laser are sent to a home-built confocal microscope available in the lab, whose main components are sketched in Figure 10. The excitation pulses at 764 nm are reflected by a dichroic mirror (FF776-Di01,

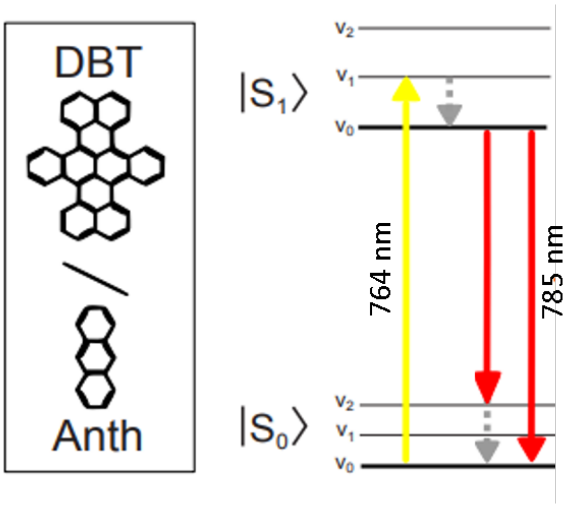


Figure 9: Chemical structure of DBT:Anth (left) and simplified energy level scheme (right), including the singlet electronic levels ($|S_0\rangle$ and $|S_1\rangle$) and their vibrational manifold. The radiative and non-radiative transitions involved in the excitation and detection scheme for the lifetime measurement are shown in solid and dashed lines, respectively. Figure adapted from [27]

Semrock) displayed in Figure 10 to the sample with an oil objective (100x oil NA= 1.4, Zeiss). The fluorescence signal collected by the same objective is then transmitted by the dichroic mirror and detected by a single-photon counting module (SPCM, AQRH-13-FC, PerkinElmer). An additional long-pass filter (LP, LPD02-785RU, Semrock) is placed in front of the detector to further cut light below 785 nm, corresponding to the energy gap between the purely electronic states – the so-called 00-zero phonon line (00-ZPL). To measure the fluorescence lifetime using the reverse TCSPC method discussed in chapter 2.3 the setup shown in figure 10 was built. Missing cables were soldered to ensure an optimal connection length. This is controlled with a LabVIEW software displayed in Figure 11 developed together with Kevin Thommes. "Start Meas" uses the bias controller to determine the optimal bias voltage before starting a fluorescence lifetime measurement. The NI card sends a continuous TTL high to the WFG for the duration of the measurement ("Meas Time") to trigger optical pulses. Once a photon is detected by the SPCM the time tagger starts the clock. The second output of the RF-pulse generator stops the time tagger. Due to the measurement method, the data is saved time reversed which can be seen in Figure 11. The "Start Bias" button can be used to adjust the bias for other purposes without beginning a measurement.

In the following, the optimal optical pulse parameters to perform the fluorescence lifetime measurement are discussed. From literature, it is known that the lifetime of DBT:Anth is about 4 ns [1, 2]. A pulsed source should fulfil the following criteria.

- **pulse amplitude**

  The pulse amplitude is chosen according to the saturation intensity of the molecular system,

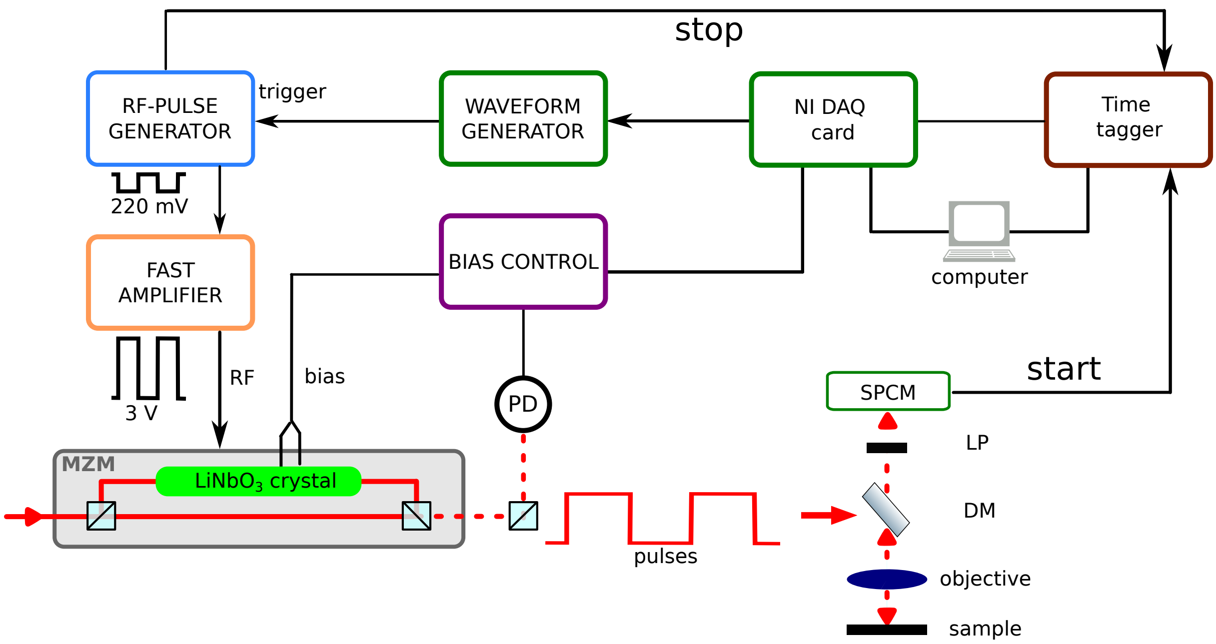


Figure 10: The epifluorescence microscope setup used collimates the excitation and fluorescence signal simultaneously because they get aligned with the same objective. A dichroic filter reflects the incoming laser onto the objective. The stokes shifted signal from the molecule is transmitted onto the detector, while light with shorter wavelengths is reflected back. The long pass (LP) filter is needed since the dichroic filter does not block all the unwanted light.

which is around $80\,\mathrm{kW\,cm^{-2}}$ [1]. This corresponds to a power of around $500\,\mu\mathrm{W}$ for an excitation spot area of about $0.5\,\mu\mathrm{m}^2$.

- **pulse width**

  A pulse width on the order of the lifetime gives the best signal-to-noise ratio since the system goes close to saturation. In our case, a pulse width between 4 ns and 7 ns is optimal

- **repetition rate**

  To properly fit the fluorescence decay curve with a single exponential, enough data points close to the zero level are needed. This can be achieved using a low repetition rate, which however increases the overall acquisition time. A reasonable compromise is to choose the time between subsequent pulses to be five to ten times the expected fluorescence lifetime. In our case, this corresponds to repetition rates between 20 MHz to 40 MHz.

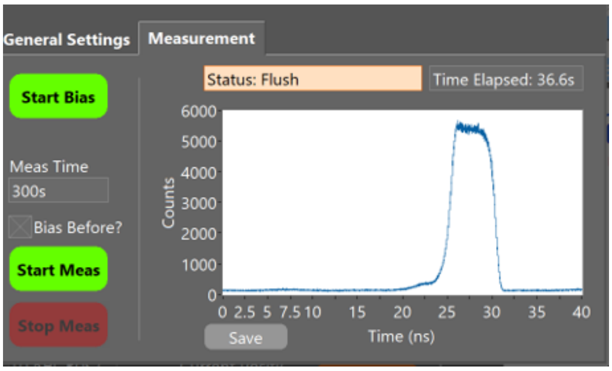


Figure 11: Software for the fluorescence lifetime measurement developed together with Kevin Thommes. The pulse is displayed time inverted since the reverse TCSPC method was used.

4 Results

This chapter presents the measurements performed with the setups described in chapter 3 and discusses their results. The first experiment studies the general properties of the Mach-Zehnder modulator (MZM) that can be extracted from the characteristic curve. Then, the features of optical pulses generated by both the 785 nm and 764 nm laser are discussed. Finally, the result of the lifetime measurement is presented.

4.1 Characteristic curve of the Mach-Zehnder modulator

The characteristic curve measured with the setup shown in Figure 12 was measured to determine the optimal voltage inputs and characteristics of the MZM. A voltage ramp from $-10\,\mathrm{V}$ to $10\,\mathrm{V}$ with a repetition rate of 100 Hz was sent from the waveform generator to the bias input of the MZM. The output of the MZM was measured with a homemade photodiode with a responsivity curve as the one shown in Figure 6. The characteristic curve for both wavelengths can be seen in Figure 13 The data is normalized by the maximum value.

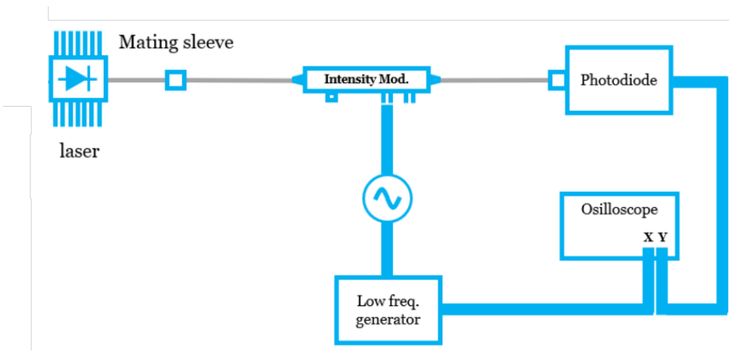


Figure 12: Setup for the measurement of the characteristic curve. The WFG uses a T-piece to send a voltage ramp to the MZM and the x-channel of the oscilloscope. The homemade PD measures the output intensity and sends the corresponding voltage to the y-channel of the oscilloscope.

From this V_π and the extinction ratio were calculated according to chapter 2.1.2. They were

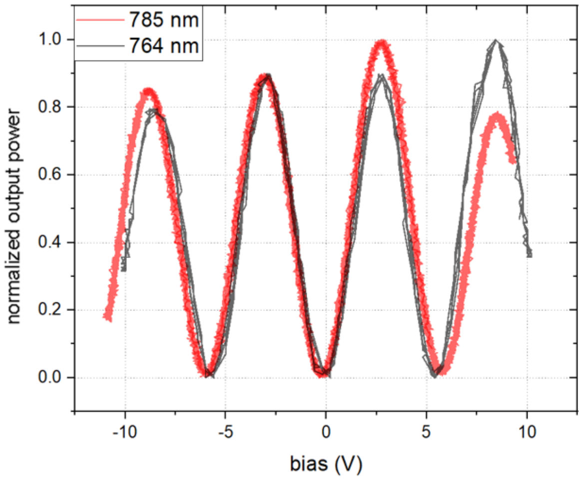


Figure 13: Characteristic curve of the MZM. Here shown for $\lambda_{\text{laser}} = 785\,\text{nm}$ which corresponds to $V_\pi = (3.0 \pm 0.1)\,\text{V}$ and $\lambda_{\text{laser}} = 764\,\text{nm}$ which corresponds to $V_\pi(764) = (2.82 \pm 0.01)\,\text{V}$. Applying V_π leads to phase change of π in between both arms of the MZM.

measured at the extrema closest to $V_{\text{bias}} = 0\,\text{V}$. This is done to reduce the bias drift, as explained hereafter. V_π is calculated from the difference between the nearest minimum and maximum of the characteristic curve resulting in

$$V_\pi(785\,\text{nm}) = (3.0 \pm 0.1)\,\text{V}$$

for the 785 nm laser. This is comparable to the factory measured $V_\pi = 3.1\,\text{V}$ at 850 nm wavelength [13]. This measurement was repeated for the 764 nm laser.

$$V_\pi(764\,\text{nm}) = (2.82 \pm 0.01)\,\text{V}$$

This result is consistent with the theory according to equation (2) $\frac{V_\pi}{\lambda} = -\frac{g}{r_{33} n_3^3 L \Gamma}$. This predicts that the ratio of V_π and λ stays constant for different laser wavelengths. This is fulfilled for the two used wavelengths within the range of uncertainty.

From the difference between minimum and maximum of the characteristic curve, the extinction ratio (ER) is calculated.

$$\text{ER}\,(\text{dB}) = P_{\max}\,(\text{dB}) - P_{\min}\,(\text{dB})$$

For the minimum/maximum closest to $V_{\text{bias}} = 0\,\text{V}$

$$\text{ER}(@785\,\text{nm}) = (24.7 \pm 0.2)\,\text{dB}$$

$$\text{ER}(@764\,\text{nm}) = (23.4 \pm 0.2)\,\text{dB}$$

A higher extinction ratio gives a better signal-to-noise ratio for the fluorescence lifetime. Despite the used wavelengths 785 nm and 764 nm being close or below the minimum MZM operating wavelength (780 nm) [13] the measured extinction ratio is above 20 dB given by the Acceptance Test Report shown in Figure 24. The performance of a MZM gets worse below the minimum operating wavelength due to the photorefractive and other nonlinear effects, which change the refractive index of the material when light passes through. Two observations were made which can be investigated in further research. At higher bias voltages, the value for V_π becomes smaller by up to 10 %. For laser wavelength $\lambda = 764$ nm and $V_{\text{bias}} = 8$ V V_π becomes 2.62 V instead of 2.82 V. The extinction ratio also changes depending on the bias voltages and the used wavelength. This could be partly caused by higher-order nonlinear effects in the crystal which occur at higher voltages.

Insertion loss

The insertion loss quantifies the amount of light lost from the incloupling into the MZM. To measure the insertion loss of the MZM the laser is coupled into a fibre and the power P_{ref} behind the fibre is measured. Then this fibre is connected to the fibre of the MZM and the power P_{out} after the MZM is measured. The insertion loss is therefore defined as

$$\text{IL (dB)} = P_{\text{ref}}(\text{dB}) - P_{\text{out}}(\text{dB})$$

The losses from the mating sleeve are between 0 dB to 1 dB [22]. From this follows

$$\text{IL (dB)} = 5.5\,\text{dB to } 6.5\,\text{dB}$$

This is in agreement with the factory measured value 5.9 dB from Figure 24.

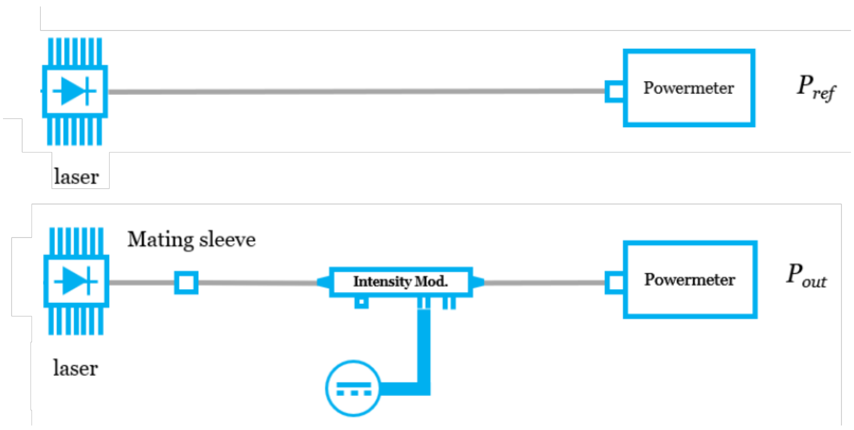


Figure 14: To measure the insertion loss of the MZM the laser is coupled into a fibre and the power P_{ref} behind the fibre is measured. Then this fibre is connected to the fibre of the MZM and the power P_{out} after the MZM is measured. The insertion loss is then defined as IL (dB) $= P_{\text{ref}}(\text{dB}) - P_{\text{out}}(\text{dB})$

Bias drift

The bias drift is the change of V_{bias} over time. For faster drifts, V_{bias} has to be adjusted more

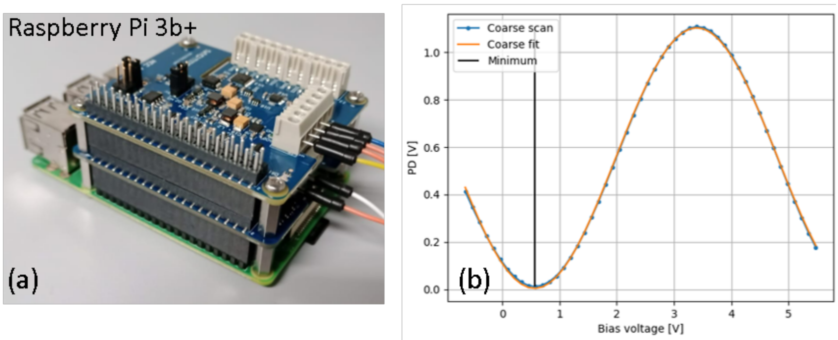


Figure 15: (a) The bias controller was implemented with a Raspberry Pi 3b+. (b) Measured data and fit of the characteristic curve by the Raspberry Pi.

frequently to avoid signal distortions. To estimate the bias drift for 764 nm the characteristic curve was acquired every 1 min over 110 min from which V_{bias} and V_π are calculated. The results are shown in Figure 17 The measurement was repeated with the Raspberry Pi which saves the

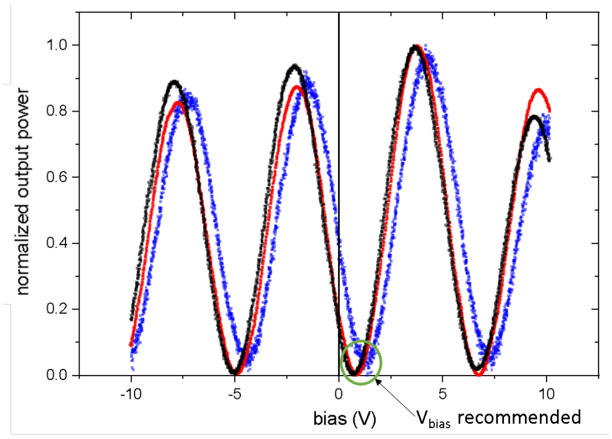


Figure 16: The bias drift is the rigid shift over time of the characteristic curve. It is caused by thermal inhomogeneities, ageing of the crystal, photorefractive effects and static electrical charge accumulation [22]. These curves were taken with the 785 nm laser by applying a voltage ramp with the WFG from -10 V to 10 V with a repetition rate of100 Hz to the bias input of the MZM. The data were normalized by the maximum value.

applied optimal bias voltage and the calculated value for V_π. Bias drift (a) and V_π (b) over time on a logarithmic scale for laser wavelength 764 nm with $P_{in} = 10$ mW. (a) The y-axis shows the smallest absolute bias voltage corresponding to an output minimum of the MZM. The data is heuristically fitted with a double exponential decay

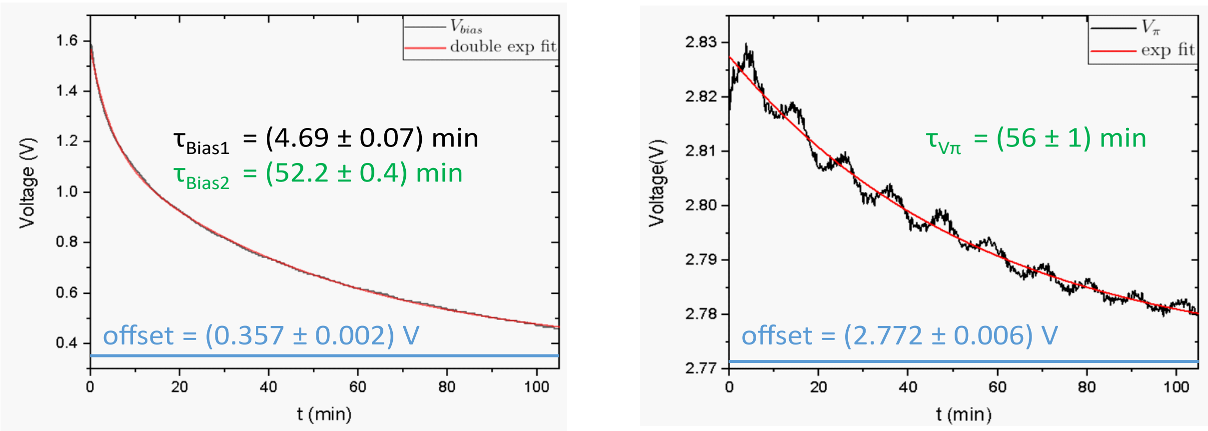
$V_{\text{bias}}(t) = \text{A}_1 \cdot \exp\left(\frac{-t}{\tau_{bias_1}}\right) + \text{A}_2 \cdot \exp\left(\frac{-t}{\tau_{bias_2}}\right) + \text{V}_{\text{bias}}$.

On the y-axis is V_π between the extrema of the characteristic curve closest to zero. The data is also heuristically fitted with an exponential decay $V_\pi(t) = \text{B} \cdot \exp\left(\frac{-t}{\tau_\pi}\right) + \text{V}_\pi$.

fitting coefficient	value
V_{bias}	(0.357 ± 0.002) V
A_1	(0.385 ± 0.003) V
τ_{bias1}	(4.69 ± 0.07) min
A_2	(0.825 ± 0.001) V
τ_{bias2}	(52.2 ± 0.4) min
R^2_{adj}	0.999

fitting coefficient	value
V_π	(2.772 ± 0.006) V
B	(0.06 ± 0.01) V
τ_π	(56 ± 1) min
R^2_{adj}	0.983

The fit shows that V_{bias} and V_π have a similar decay parameter τ_{bias2} and τ_π. The periodic distortion in Figure 17b for V_π may be caused by thermal fluctuations, however these can't be seen for V_{bias}.



(a) (b)

Figure 17: Bias drift (a) and V_π (b) over time on a logarithmic scale for laser wavelength 764 nm with $P_{in} = 10\,\text{mW}$. (a) The y-axis shows the smallest absolute bias voltage corresponding to an output minimum of the MZM. The data is fitted with a double exponential decay $V_{\text{bias}}(t) = A_1 \cdot \exp\left(\frac{-t}{\tau_{bias_1}}\right) + A_2 \cdot \exp\left(\frac{-t}{\tau_{bias_2}}\right) + V_{\text{bias}}$.
(b) On the y-axis is V_π between the extrema of the characteristic curve closest to zero. The data is fitted with an exponential decay $V_\pi(t) = B \cdot \exp\left(\frac{-t}{\tau_\pi}\right) + V_\pi$.

The drift happens because applying a DC-voltage cause a charge transport in the crystal, which partially compensates for the applied voltage. Other factors are environmental changes like fluctuations in humidity and temperature. The drift is faster for higher absolute voltages [22].

4.2 Optical pulses

After determining V_π and how to compensate the bias drift the generated optical pulses were analysed. An ideal pulsed source would emit rectangular pulses with negligible width. Real pulses deviate from that model in different ways, as schematically shown in Figure 18. It is therefore important to determine the following parameters.

Important characteristics:

- **pulse width** is measured between the 50% level of the amplitude of the rising and falling edge
- **The rise (fall) time** defined as the time for the pulse to go from the 10% (90%) to the 90% (10%) mark
- **jitter** is the deviation from true periodicity
- **overshoot** is the amount that the rising edge exceeds the average amplitude of the pulse.
- **after pulse** is the relation between the amplitude of the after pulse to the amplitude of the main pulse.

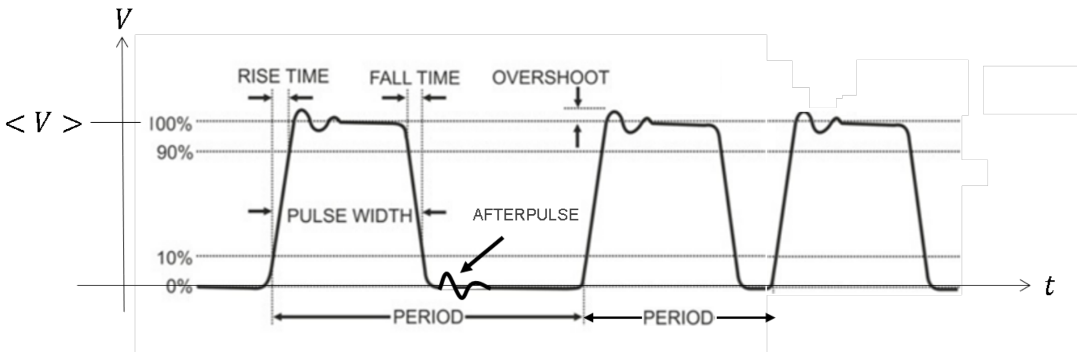


Figure 18: An ideal pulse is rectangular with zero width at a fixed repetition rate. Real pulses deviate from that model. So width, rise/fall time, overshoot, after pulse and jitter have to be taken into account. Figure modified from [35].

Electrical and optical pulses were analysed for different pulse widths and repetition rates showing comparable results as the one summarized in the Table 2 for the case of the 5 ns with a repetition of 1 kHz. From the graph in Figure 19 it can be concluded that the transformation from electrical to optical pulses preserves most of its attributes like width, rise and fall time. The data was shifted to zero and normalised by the maximum value. The following plots show the rise and fall time for

pulse	width [ns]	rise time [ps]	fall time [ps]	jitter [ps]	overshoot [%]	afterpulse [%]
EP	4.906 ± 0.006	110 ± 5	118 ± 8	170 ± 10	13	2
OP	4.894 ± 0.006	113 ± 4	121 ± 7	230 ± 40	7	5

Table 2: Pulse width, rise/fall time, jitter, overshot and afterpulse for EP and OP from the 785 nm laser

optical and electrical pulses of different widths. Different trigger shapes (sinus, rectangular, pulse) and repetition frequencies were tested to reduce the jitter of the pulses. The rise time of the

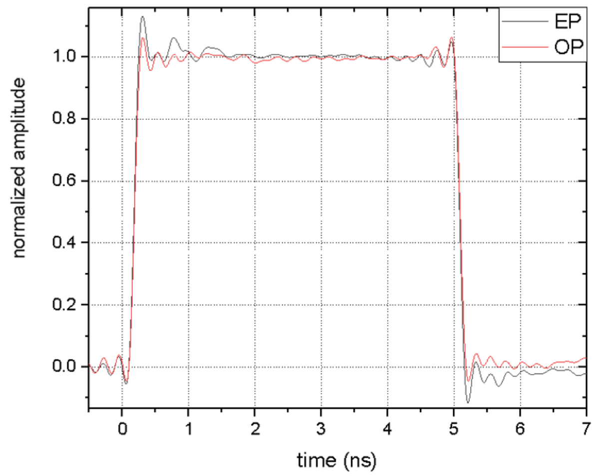


Figure 19: Normalized electrical and optical pulse with a width of 5 ns. The electrical pulse is measured before amplification. The graph shows that the transformation from electrical to optical pulses preserves most of its attributes like width, rise and fall time.

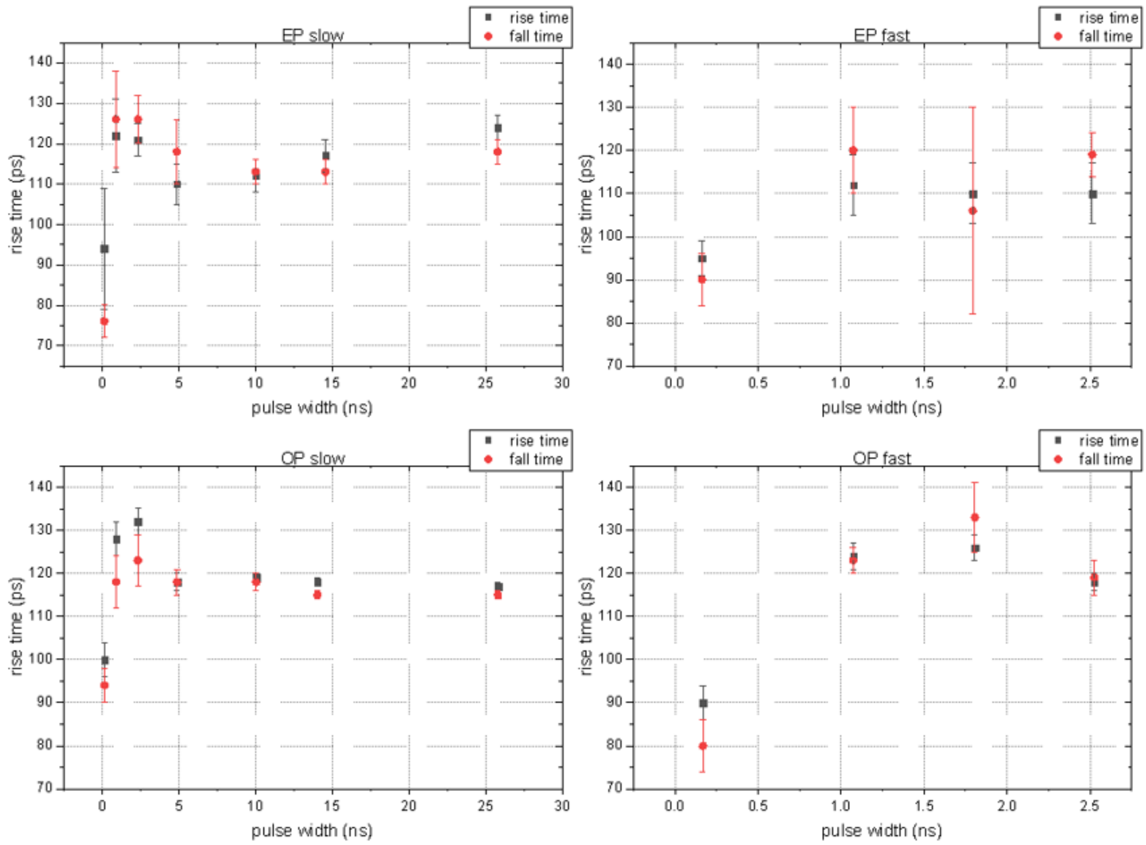


Figure 20: The rise and fall time shown for electrical (EP) and optical (OP) pulse with widths from 0.16 ns to 25 ns. The plots are shown for the "slow" and "fast" range of the pulse generator. The "fast" range is for high repetition rates, and a "slow" range for pulse widths above 2.5 ns. The rise and fall time are lower than 130 ps for the whole range. The values for rise and fall time have overlapping uncertainty intervals for the same pulse width.

trigger is an important characteristic for that purpose. The rectangular trigger shape was chosen because it had the lowest rise time of (4.796 ± 0.005) ns. The fall time is not important since the PG triggers on the rising edge of the trigger [36]. It is important for the lifetime measurement

trigger	rise time [ns]	fall time [ns]
square	4.796 ± 0.005	4.319 ± 0.005
sinus	4.796 ± 0.005	7.488 ± 0.005
pulse	6.003 ± 0.005	6.988 ± 0.005

Table 3: Rise and fall time for different trigger shapes.

that the jitter is negligible compared to the pulse lengths. Otherwise, pulses can overlap. Also, the fall time has to be smaller than the lifetime, otherwise, the decay can't be measured. For $\lambda = 785\,\text{nm}$ the values are appropriate.

$$\text{pulse distance} \gg \text{jitter} \qquad\qquad \text{lifetime} \gg \text{fall time}$$

$$18\,\text{ns} \gg 250\,\text{ps} \qquad\qquad 5\,\text{ns} \gg 231\,\text{ps}$$

Changing laser wavelength to 764 nm :
The lifetime measurement is done with a different laser wavelength $\lambda = 764\,\text{nm}$ to get off-resonant excitation for a dibenzoterrylene molecule embedded in a nanocrystal of anthracene (DBT:Anth). This is outside the operating range of the MZM, so the pulses have worse properties compared to the case of $= 785\,\text{nm}$. To measure the time difference between the excitation pulse and fluorescence signal, a time tagger and an SPCM are used. Figure 21 compares the optical pulses measured with the fast PD and oscilloscope from the old setup and time tagger and an SPCM from the lifetime setup. The data was shifted to zero and normalised with the maximum value.
The rise/fall time of the SPCM/time-tagger measured pulse is much longer compared to the

pulse	width [ns]	rise time [ps]	fall time [ps]	jitter [ps]	overshoot [%]	afterpulset [%]
PD	4.970 ± 0.006	400 ± 5	300 ± 8	180 ± 90 [1]	13	3
SPCM	5.4 ± 0.1	1270 ± 10	2180 ± 15	80 [2]	7	2

Table 4: comparison of optical pulses measured with a fast PD/Oscilloscope and SPCM/time-tagger for $\lambda = 764\,\text{nm}$.

pulses measured with the fast PD and the fall time can't be neglected compared to lifetime anymore. This might give an incorrect lifetime value, but the setup should be able to at least detect a fluorescence signal as a proof of concept.

[1] The jitter was determined with the oscilloscope by measuring the deviation of the periodicy over time.
[2] The jitter is taken from the specs of the time tagger.

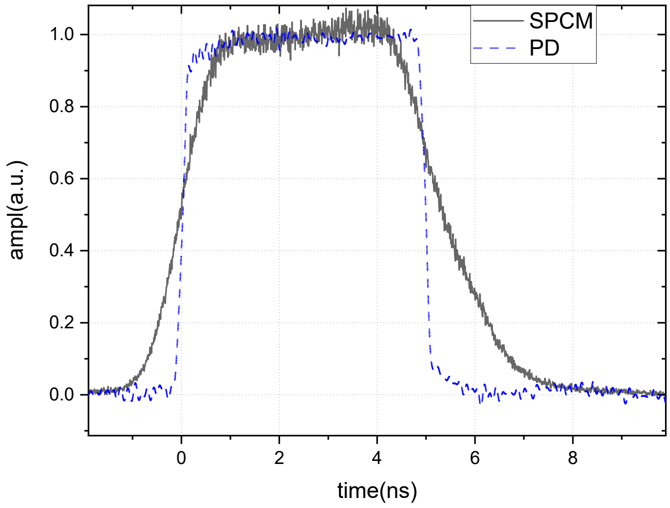


Figure 21: Comparison of the same 5 ns pulses (30 MHz repetition rate) from the 764 nm laser detected with the fast PD and the oscilloscope (blue curve) and with the SPCM and the time tagger (black curve).

4.3 DBT:Anth fluorescence lifetime

For the lifetime measurement, the setup of Figure 10 is used. The laser current was set to 90 mA and the laser temperature to 20 °C. The excitation pulses have a width of 5 ns and a repetition rate of 30 MHz. To measure only a single exponential decay with a good signal-to-noise ratio, the sample is scanned for an isolated bright molecule. In Figure 22 a-c the scanned-confocal image the scattered light and the white light image are shown.

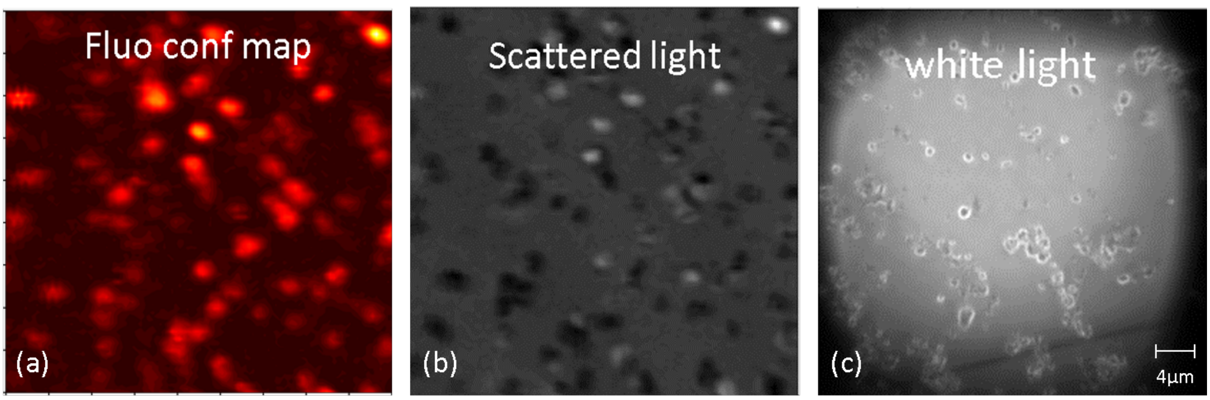


Figure 22: A 40x40 µm area is scanned on the sample to locate fluorescing DBT-molecules in isolated Anthracene nanocrystals. (a) Scanning confocal map with the laser in CW-mode. The MZM modulator is set to maximum transmission. This shows fluorescing molecules. (b) Image of the scattered light. Behind the dichroic mirror is an additional long pass to remove the rest of the excitation signal. For this measurement, the long pass is completely closed to only measure stray light. (c) White light image using an electron-multiplying charge-coupled device (EMCCD) camera.

To obtain the lifetime the data was normalized by the maximum value and the fluorescence curve was fitted with an exponential decay. The data interval for the fit starts after the fluorescence curve and the excitation pulse falling edge deviate and stops when the fluorescence curve reaches the ground level. The curve shows a fluorescence decay. This can be seen from the deviation of

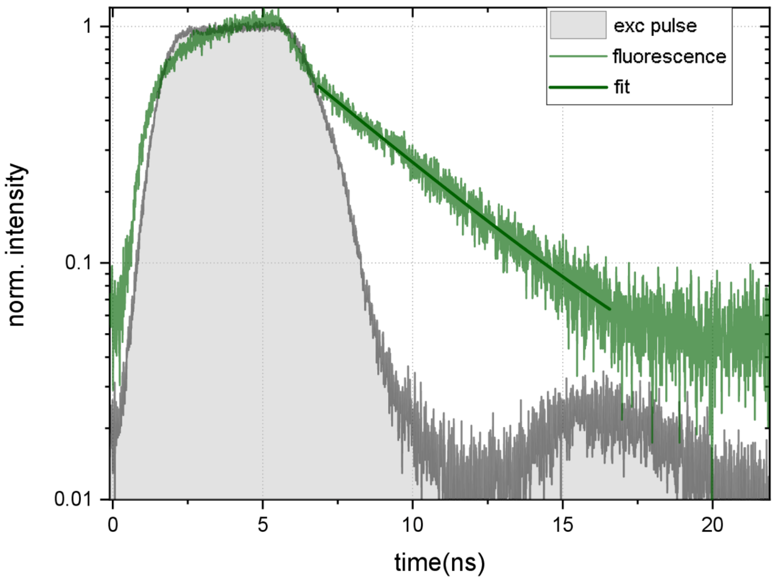


Figure 23: These graphs show the excitation pulse and the fluorescence signal measured with an SPCM and a time tagger. The deviation of the fluorescence signal from the excitation pulse shows that fluorescence was measured and that the setup can determine the lifetime of DBT:Anth. The lifetime can be measured by fitting the falling edge of the fluorescence signal once it deviates from the excitation pulse. $I(t) = \mathrm{C} \cdot \exp\left(\frac{-t}{\tau}\right) + \mathrm{I}_0$. With fitting coefficients $\mathrm{I}_0 = 0.01 \pm 0.01$, $\mathrm{C} = 2.9 \pm 0.1$, $\tau = (4.1 \pm 0.5)\,\mathrm{min}$ and $\mathrm{R}^2_{\mathrm{adj}} = 0.961$. The measured lifetime $\tau = (4.1 \pm 0.5)\,\mathrm{ns}$ is compatible with the literature value of $\tau = (4.1 \pm 0.4)\,\mathrm{ns}$.

the falling edge of the lifetime curve compared to the excitation pulse. This shows the setup can be used to measure the fluorescence lifetime. The lifetime value for DBT:Anth is

$$\tau = (4.1 \pm 0.5)\,\mathrm{ns}$$

The measured value is compatible with the literature value of $\tau = (4.1 \pm 0.4)\,\mathrm{ns}$ [1, 2].

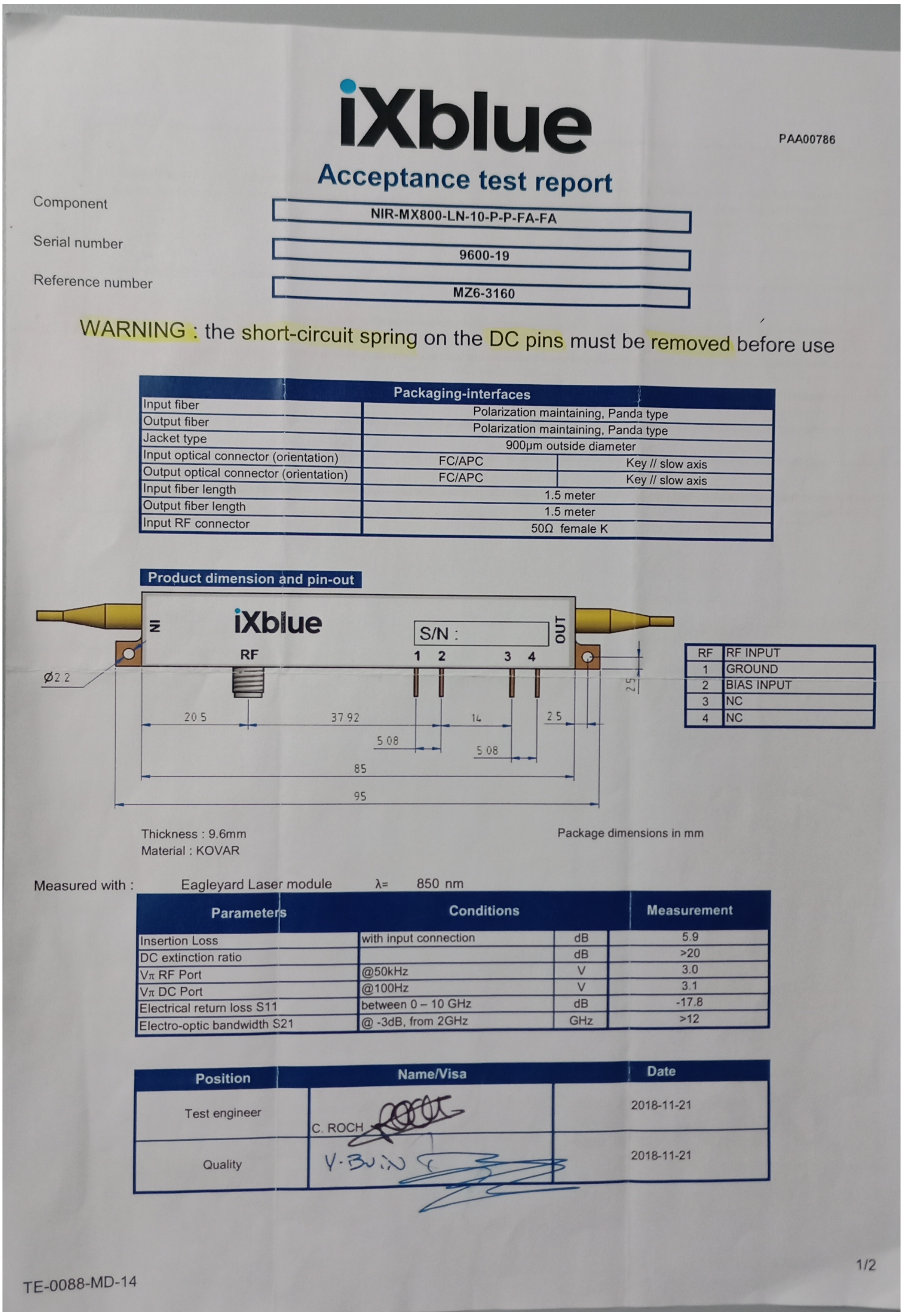
5 Conclusions and Outlook

The goal of this thesis was to implement a nanosecond pulsed light source using a Mach-Zehnder modulator (MZM) in conjunction with a continuous-wave laser from 0.160 ns to 25 ns. A waveform generator was used to trigger an electric pulse generator. The output was then sent to the fast amplifier to drive the MZM from minimum to maximum optical throughput. To compensate for the time-dependent offset of the MZM, a bias controller was implemented. This device scans the output of the MZM and continuously adjusts the offset of the voltage supply to achieve the optimal extinction ratio of the optical pulses. This allows the transformation of electrical pulses into optical pulses. The generated optical pulses were detected with a fast PD and oscilloscope to analyse their difference from an ideal pulsed source. Different trigger shapes were tested to minimize the jitter. The rectangular trigger gave the best results. As an application, we use the modulated laser source for measuring the fluorescence lifetime of a single molecule of DBT:Anth. For this, optical pulses of 5 ns width and 30 MHz repetition rate were generated. Using an SPCM and a time-tagger the time difference between the laser excitation pulse and the fluorescence signal was determined. By repeating this measurement over time, the fluorescence signal was reconstructed and the lifetime of DBT:Anth was fit with a single exponential decay. The calculated lifetime is $\tau_{exp} = (4.1 \pm 0.5)$ ns. This value is compatible with the literature one of (4.1 ± 0.4) ns [1, 2].

In the following, some improvements are suggested to optimize the measurement. The signal-to-noise can be increased by shielding the SPCM from stray light and using a special cladded fibre to reduce the background counts. The optical pulse rise-time measured via SPCM and time-tagger is four times longer compared to the measurement with PD and oscilloscope. If the fall time is too long, the lifetime cannot be correctly measured, since the excitation pulse falls too slowly compared to the fluorescence signal. The measured value agrees with expectations as discussed above but it is recommended to repeat the measurement with a different SPCM with a better time resolution and to compare the results. The setup can also be used for other wavelengths, but some problems arise for shorter wavelengths. The rise/fall time of the optical pulses becomes larger and the input power must be reduced to avoid additional unwanted non-linear effects in the crystal of the modulator. The MZM might drift so fast that the currently employed method for the bias controller can no longer be used. The worse performance at shorter wavelengths is due to the photorefractive effect and the fact that Mach-Zehnder modulators are mainly used in telecommunications, where wavelengths of 1500 nm are used. Therefore, there is not much research on devices for wavelengths below 780 nm.

A Appendix

A.1 MZM Acceptance Test Report



iXblue

PAA00786

Acceptance test report

Component	NIR-MX800-LN-10-P-P-FA-FA
Serial number	9600-19
Reference number	MZ6-3160

WARNING : the short-circuit spring on the DC pins must be removed before use

Packaging-interfaces		
Input fiber	Polarization maintaining, Panda type	
Output fiber	Polarization maintaining, Panda type	
Jacket type	900µm outside diameter	
Input optical connector (orientation)	FC/APC	Key // slow axis
Output optical connector (orientation)	FC/APC	Key // slow axis
Input fiber length	1.5 meter	
Output fiber length	1.5 meter	
Input RF connector	50Ω female K	

Product dimension and pin-out

RF	RF INPUT
1	GROUND
2	BIAS INPUT
3	NC
4	NC

Thickness : 9.6mm
Material : KOVAR

Package dimensions in mm

Measured with : Eagleyard Laser module λ= 850 nm

Parameters	Conditions		Measurement
Insertion Loss	with input connection	dB	5.9
DC extinction ratio		dB	>20
Vπ RF Port	@50kHz	V	3.0
Vπ DC Port	@100Hz	V	3.1
Electrical return loss S11	between 0 – 10 GHz	dB	-17.8
Electro-optic bandwidth S21	@ -3dB, from 2GHz	GHz	>12

Position	Name/Visa	Date
Test engineer	C. ROCH	2018-11-21
Quality	V. BUIN	2018-11-21

1/2

TE-0088-MD-14

Figure 24: Acceptance Test Report of the modulator tested with laser wavelength 850 nm. The measured values can only be used as an estimate, since the used wavelengths are ≈ 100 nm lower.

A.2 Bias controller software

Listing 1: Python code for the bias controller

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import curve_fit
import daqhats as daq
import time
from datetime import datetime
import os
from scipy.signal import argrelextrema


#send signal from PFI12
#declares adress for input and output board. 128 input, 152 output
AnalogOut = daq.mcc152(address=1)
AnalogIn = daq.mcc128(address=0)


def poly(x, x0, a, b):
                return a+b*(x-x0)**2

def f(x, A, omega, x0, y0):
        return A*np.cos(omega*(x-x0))**2+y0

def wait_for_TTL():
        AnalogOut.dio_reset()

        value_old = 0
        while True:
                value_new = AnalogOut.dio_input_read_bit(channel=7)
                #print(value_new)

                if value_new > value_old:
                        #print(f'TLL height = {value_new}')

                        return
                value_old = value_new
                #time.sleep(0.5)


def convert(seconds):
    seconds = seconds % (24 * 3600)
    hour = seconds // 3600
    seconds %= 3600
    minutes = seconds // 60
    seconds %= 60

    return "%d:%02d:%02d" % (hour, minutes, seconds)
```

```python
class PulseberryPi():

    def __init__(self, chIn, chOut):
        self.channel_in = chIn
        self.channel_out = chOut
        AnalogOut = daq.mcc152(address=1)
        AnalogIn = daq.mcc128(address=0)
        #self.bias_voltage_min = 0 # not used?
        #self.bias_voltage_max = 2 # not used?

    def write_analog_out(self, val):
        AnalogOut.a_out_write(channel=self.channel_out, value=val)

    def read_avg(self, num_avg=100):
        PD_reading = 0
        for i in range(num_avg):
            PD_reading += AnalogIn.a_in_read(channel=self.channel_in)
        return PD_reading/num_avg


    '''
    Ramps from start V to stop V with a stepsize of stepsize V
    in ramp_time s, for every point it averages over n_avg
    readings. Chooses the minimum further from the boundary
    to ensure that the true minium is inside the boundary and
    reachable with the bias voltage provided by the raspberry pi.
    Otherwise we might choose a lokal minimum, since the true
    minimum is out of bounds.
    '''
    def ramp_analog_out(self, start=0, stop=5, stepsize=0.05, \
    ramp_time=0.03, n_avg=5):
        #increase ramp_time if you encounter problems
        voltage = []
        steps = np.abs((stop-start))/stepsize+1
        delay = ramp_time/steps

        #t0 = time.perf_counter()
        direction = np.sign(stop-start)
        AnalogOut.a_out_write(channel=self.channel_out, value=start)
        time.sleep(0.02)
        scan = \
        np.arange(start, stop+direction*stepsize, direction*stepsize)
        for i, val in enumerate(scan):
            AnalogOut.a_out_write(channel=self.channel_out, value=val)
            time.sleep(delay)
            temp = self.read_avg(num_avg=n_avg)
            voltage.append(temp)
        #t1 = time.perf_counter()
        #print(t1-t0)
        return scan, voltage
```

```
##############################################################################

    def calibrate_simple(self, plot=False, mode='min',
    logging=False, num_avg=30):

        print('\n\nCalibration Mach Zehnder...')
        if mode == 'min':
            t0=time.perf_counter()
            scan_coarse, PD_coarse = self.ramp_analog_out(start=0.0,




    #def f(x, A, omega, x0, y0):
    #return A*np.cos(omega*(x-x0))**2+y0


            # Finds local minimum
            A_guess = np.max(PD_coarse)
            x0_guess = scan_coarse[np.argmax(PD_coarse)]
            try:
                # fit coarse scan with cos^2
                #p0_f = [A_guess, np.pi/(2*2.82), x0_guess, 0.014]
                #without amplifier
                p0_f = [A_guess, np.pi/(2*2.31), x0_guess, 0.004]
                #with amplifier
                popt_f, pcov_f = curve_fit(f, scan_coarse, PD_coarse,
                p0=p0_f)
                #popt optimal values and pcov covariance of the values

                x_fit = np.linspace(0, 5, 1000)
                fit = f(x_fit, *popt_f)
                # Select minimum furthest away from boundaries
                bias_voltage_minima = \
                x_fit[argrelextrema(np.array(fit), np.less)]
                bounds = np.array([0,5])[:len(bias_voltage_minima)]
                bias_voltage_cal = \
                bias_voltage_minima[np.argmax(
                np.abs(bias_voltage_minima-bounds))]


                concat_var = (
        f"Pmax = {popt_f[0]:.3f}V; "
                    f"Vpi = {np.pi/(2*popt_f[1])*2.82/2.31:.3f}V; "
                    f"x0 = {(popt_f[2]-0.53)*6.13/5:.3f}V; "
                    f"Vbias = {(bias_voltage_cal-0.53)*6.13/5:.3f}V; "
                    f"y0={popt_f[3]:.3f}V ")
                print(concat_var)
```

```
            except:
                    print('Fit failed')
                    bias_voltage_cal = scan_coarse[np.argmin(PD_coarse)]

            #AnalogOut.a_out_write(channel=self.channel_out,
            #value=bias_voltage_cal)
            #AnalogOut.a_out_write(
            #channel=self.channel_out, value= 0.45)
            AnalogOut.a_out_write(channel=self.channel_out, \
            value= bias_voltage_cal)

            t1=time.perf_counter()
            print(f'Calibration Time {t1-t0:.4f}')



        elif mode == 'min_30MHz':
            t0=time.perf_counter()
            scan_coarse, PD_coarse = self.ramp_analog_out(start=0.0,




#def f(x, A, omega, x0, y0):
#return A*np.cos(omega*(x-x0))**2+y0



            # Finds local minimum
            A_guess = np.max(PD_coarse)
            x0_guess = scan_coarse[np.argmax(PD_coarse)]
            try:
                    # fit coarse scan with cos^2
                    #p0_f = [A_guess, np.pi/(2*2.82), x0_guess, 0.014]
                    #without amplifier
                    p0_f = [A_guess, np.pi/(2*2.31), x0_guess, 0.004]
                    popt_f, pcov_f = \
                    curve_fit(f, scan_coarse, PD_coarse, p0=p0_f)
                    #popt optimal values and pcov covariance
        #of the values
                    print(f'Pmax = {popt_f[0]:.3f}V; Vpi = \
                    {np.pi/(2*popt_f[1])*2.82/2.31:.3f}V;        \
                    x0 = {(popt_f[2]-0.53)*6.13/5:.3f}V;         \
                    y0={popt_f[3]:.3f}V  ')
                    x_fit = np.linspace(0, 5, 1000)
                    fit = f(x_fit, *popt_f)
                    # Select minimum furthest away from boundaries
                    bias_voltage_minima = \
                     x_fit[argrelextrema(np.array(fit), np.less)]
                    bounds = np.array([0,5])[:len(bias_voltage_minima)]
                    bias_voltage_cal = \
                    bias_voltage_minima[np.argmax(
```

```
                    np.abs(bias_voltage_minima-bounds))]


                    concat_var = (f"Pmax = {popt_f[0]:.3f}V; "
                            f"Vpi = {np.pi/(2*popt_f[1])*2.82/2.31:.3f}V; "
                            f"x0 = {(popt_f[2]-0.53)*6.13/5:.3f}V; "
                            f"Vbias = {(bias_voltage_cal-0.53)*6.13/5:.3f}V; "
                            f"y0={popt_f[3]:.3f}V ")
                    print(concat_var)
            except:
                    print('Fit failed')
                    bias_voltage_cal = scan_coarse[np.argmin(PD_coarse)]


            #AnalogOut.a_out_write(channel=self.channel_out,
            #value=bias_voltage_cal + 0.27) #A 0.16 close to 0.17
            AnalogOut.a_out_write(channel=self.channel_out,
            value=bias_voltage_cal + 0.27)
            t1=time.perf_counter()
            print(f'Calibration Time {t1-t0:.4f}')

    elif mode == 'max':

            t0=time.perf_counter()
            scan_coarse, PD_coarse = self.ramp_analog_out(start=0.0,





            # Finds local maximum
            scan_coarse = scan_coarse[:-1]
            PD_coarse = PD_coarse[:-1]
            A_guess = np.max(PD_coarse)#change to minimum
            x0_guess = scan_coarse[np.argmax(PD_coarse)]
#change to minimum
            try:
                    # fit coarse scan with cos^2
                    #p0_f = [A_guess, np.pi/(2*2.82), x0_guess, 0.014]
                    #wihtout output amplifier
                    p0_f = [A_guess, np.pi/(2*2.32), x0_guess, 0.014]
                    #with output amplifier
                    popt_f, pcov_f = \
                    curve_fit(f, scan_coarse, PD_coarse, p0=p0_f)
                    print(f'Pmax = {popt_f[0]:.3f}V; \
                    Vpi = {np.pi/(2*popt_f[1])*2.82/2.31:.3f}V; \
                    x0 = {(popt_f[2]-0.53)*6.13/5:.3f}V; \
                    y0={popt_f[3]:.3f}V  ')
                    x_fit = np.linspace(0, 5, 1000)
                    fit = f(x_fit, *popt_f)
                    # Select maximum furthesst away from boundaries
```

```
                bias_voltage_maxima = \
                x_fit[argrelextrema(np.array(fit), np.greater)]
                bounds = np.array([0,5])[:len(bias_voltage_maxima)]
                bias_voltage_cal = \
                bias_voltage_maxima[np.argmax(
                np.abs(bias_voltage_maxima-bounds))]

                concat_var = (f"Pmax = {popt_f[0]:.3f}V; "
                        f"Vpi = {np.pi/(2*popt_f[1])*2.82/2.31:.3f}V; "
                        f"x0 = {(popt_f[2]-0.53)*6.13/5:.3f}V; "
                        f"Vbias = {(bias_voltage_cal-0.53)*6.13/5:.3f}V; "
                        f"y0={popt_f[3]:.3f}V ")
                print(concat_var)
        except:
                print('Fit failed')
                bias_voltage_cal = scan_coarse[np.argmax(PD_coarse)]

        AnalogOut.a_out_write(channel=self.channel_out,
        value=bias_voltage_cal)
        t1=time.perf_counter()
        print(f'Calibration Time {t1-t0:.4f}')

else:
        print('Invalid calibration mode')


if plot:
        #print(popt_f)
        #plt.figure()
        try:
                plt.plot((scan_coarse-0.53)*6.13/5,
                PD_coarse, '.-', label='Coarse scan')
                plt.plot((scan_coarse-0.53)*6.13/5,
                f(scan_coarse, *popt_f), label='Coarse fit')
                plt.vlines((bias_voltage_cal-0.53)*6.13/5,
                np.min(PD_coarse), np.max(PD_coarse), label='Minimum',
                color='black')
                plt.grid()
                plt.legend()
                plt.xlabel('Bias voltage [V]')
                plt.ylabel('PD [V]')
                #plt.show()




        except:
                print('could not fit')
        plt.show()
# add A_guess to plot maximum of curve
if logging:
        now = datetime.now()
```

```
        #this should plot in the same folder for an hour.
        dt_string = now.strftime("%Y_%m_%d")
        #add  %H for hours_%M for minutes, %S for seconds
        dt_string2 = now.strftime("%Y_%m_%d__%H_%M_%S")
        # save plottime

        if not \
        os.path.exists('Logging/' + str(dt_string) + '/plot'):
                os.makedirs('Logging/' + str(dt_string) + '//plot')
        if not os.path.exists('Logging/' + str(
    dt_string) + '/data'):
                os.makedirs('Logging/' + str(dt_string) + '/data')
                file_object_bias = open('Logging/' + str(dt_string) + \
                 '/data/bias_cal_voltages' + \
                  str(dt_string) + '.txt', 'a+')
                  #save cal. point and time
                file_object_bias.write("{0};{1};{2};{3};{4};{5}\n" \
                .format('time in s',
                ' Pmax in V', 'Vpi in V', 'x_0 in V','Vbias in V' ,
'y0 in V'))



        current_time = time.time()
        t_3 = []
        bias_voltage_cal_ = []
        bias_voltage_cal_.append(bias_voltage_cal)
        t_3.append(current_time)
        time.time()
        bias_cal = zip(t_3, bias_voltage_cal_)
        bias_plot = zip(scan_coarse, PD_coarse)

        #use this to check that
        #for (scan_coarse, PD_coarse) in bias_plot:
        #        print(scan_coarse)
        #        print(PD_coarse)

        #for items in PD_coarse:
        #        print(items)

        #plt.savefig('Logging/' + str(dt_string) + '/plot/plot'
        #+ str(dt_string) +  '.png')       # save plotpicture
        file_object_bias = open('Logging/' + str(dt_string) + \
        '/data/bias_cal_voltages' + str(dt_string) + '.txt', 'a+')
        # save cal. point and time
        #file_object_bias.write("{0};{1};{2};{3};{4}\n".format(
        #'time in s',' Pmax in V', 'Vpi in V', 'bias in V', 'y0'))
        file_object_bias.write("{0};{1};{2};{3};{4};{5}\n".format(
        current_time, popt_f[0],np.pi/(2*popt_f[1])*2.82/2.31,(
        popt_f[2]-0.53)*6.13/5,(
bias_voltage_cal-0.53)*6.13/5,popt_f[3]))
```

```
                with open('Logging/' + str(dt_string) + '/plot/plotdata_'
                + str(dt_string2) + '.txt', 'a+') as biasplot:
                        for (scan_coarse,PD_coarse) in bias_plot:
                                biasplot.write("{0};{1}\n".format((
                                scan_coarse-0.53)*6.13/5,PD_coarse))
                biasplot.close()
                file_object_bias.close()

                print('Calibration done')

                #return (bias_voltage_cal + 0.531) # for 30 MHz
                return (bias_voltage_cal)                      # no adjustments



        V_min = 0 # minimale bias voltage
        V_max = 5 # max bias voltage
        time1 = []#*t_max
        bias1 = []#*t_max
        t_0=time.perf_counter()
        while (t_max - (time.perf_counter() - t_0) > 0):

                time1.append(time.perf_counter() - t_0)
                bias1.append(str(AnalogIn.a_in_read(
                channel=self.channel_in)))#
                #"{:.2f}".format(AnalogIn.a_in_read(
#channel=self.channel_in)
                #t_1 = time.perf_counter()
                AnalogOut.a_out_write(
                channel=self.channel_out, value= 5 * np.random.random())
                #y = AnalogIn.a_in_read(channel=self.channel_in)


        plt.plot(time1, bias1, '.', label='Bias drift')
        plt.xlabel('time [s]')
        plt.ylabel('Bias [V]')
        print('plot created')
        plt.show()




#####################################################################
#choose an option
#####################################################################
#create instance of pulseberryPi, ChIn 5: flexible BNC,
 4: PD sma connector
#                                   ChOut 1: flexible BNC, 0: MZ bias
ixBlue = PulseberryPi(chIn=5, chOut=0)
```

```
example='Calibrate_in_Intervalls'
#choose what the raspberry should do
#example= 'Set_voltage'
if example=='Set_voltage': # set voltage from 0 to 5
        ixBlue.write_analog_out(0)

''' check the n_avg constant
if example=='Read_voltage':
        reading = ixBlue.read_avg(n_avg=10)
        print(reading, 'V')
'''

if example=='Plot_ramp':
        voltage_ramp, PD_voltage = ixBlue.ramp_analog_out(start=0,
                stop=5, stepsize=0.1, ramp_time=10, n_avg=1)
        plt.figure()
        plt.plot(voltage_ramp, PD_voltage, 'o-') # o# for scatter plot
        plt.xlabel("output voltage")
        plt.ylabel("input voltage")
        plt.title('Raspberry Pi reads it\'s own voltage ramp')
        plt.show()
        time.sleep(4)
        plt.close()



if example=='Calibrate_once':
        AnalogOut.a_out_write(channel=1, value=0)
        plt.figure()
        bias_voltage_min = ixBlue.calibrate_simple(plot=True,
                                logging=True,mode='min')
        plt.show()
        AnalogOut.a_out_write(channel=1, value=5)
        time.sleep(2)
        AnalogOut.a_out_write(channel=1, value=0)


if example=='Calibrate_when_TTL':
        t0 = time.perf_counter()
        while True:
                wait_for_TTL()
                #plt.figure()
                bias_voltage_min = ixBlue.calibrate_simple(plot=False,
                                logging=True, mode='min')
                # send signal to NI-card
                AnalogOut.a_out_write(channel=1, value=0)
                AnalogOut.a_out_write(channel=1, value=5)
                time.sleep(0.2)
                AnalogOut.a_out_write(channel=1, value=0)
                print(f'time running: {convert(int(time.perf_counter() - t0))} ')
                #plt.show()
```

```
if example=='Calibrate_in_Intervalls':
    t0 = time.perf_counter()
    while True:
        bias_voltage_min = ixBlue.calibrate_simple(plot=False,
                                logging=True, mode='min')
        print(f'time running: {convert(int(time.perf_counter() - t0))} ')
        time.sleep(30) #set time intervalls
```

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Declaration of Authorship

I hereby confirm that I have authored this Bachelor's thesis independently and without the use of others other than the indicated sources. All passages which are literally or in general matter taken out of publications or other sources are marked as such.

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