COMPARATIVE ANALYSIS OF DIFFERENT ELECTRO-OPTICAL INTENSITY MODULATOR CANDIDATES FOR THE NEW 40 GHz BUNCH ARRIVAL TIME MONITOR SYSTEM FOR FLASH AND EUROPEAN XFEL#

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Abstract

The currently installed Bunch Arrival time Monitors (BAMs) at the Free electron LASer in Hamburg (FLASH) achieved a time resolution of less than 10 fs for bunch charges higher than 500 pC. In order to achieve single spike FEL pulses [1] at FLASH, electron bunch charges down to 20 pC are of interest [4]. With these BAMs the required time resolution is not reachable for bunch charges below 500 pC [5]. Therefore, new pickups with a bandwidth from DC up to 40 GHz are designed and manufactured [6, 7, 8]. The signal evaluation takes place with a time-stabilized reference laser pulse train which is modulated by an Electro-Optical intensity Modulator (EOM) in dependency on the pickup signal. The new high bandwidth BAM system also requires new high bandwidth EOMs for the electro-optical frontend. The available selection of commercial EOM candidates for the new frontend is very limited. Furthermore, the EOMs are designed for cw laser, however the BAM system use a pulsed laser with a peak power in the order of 100 W. In this paper we present a comparison between different EOM candidates for the new electro-optical frontend.

INTRODUCTION

FLASH is a source of short and extremely bright photon pulses tunable within a wavelength range from 4.2 to 45 nm [2, 3]. In order to reach FEL pulses with a duration of a single optical mode at FLASH, electron bunches with a duration of a few fs are required. In order to create such a short bunch it is necessary to reduce the bunch charge down to 20 pC to avoid elongation by space charge forces [4]. The currently used Bunch Arrival Time Monitor (BAMs) at FLASH achieved a time resolution better than 10 fs for bunch charges higher than 500 pC [5]. Because of the design and the limited bandwidth of 10 GHz, the time resolution degrades strongly for bunch charges below 200 pC [5]. Therefore, a new pickup with a bandwidth of 40 GHz has been developed [6, 7, 8] and installed at FLASH. Beside the new pickup, an electro-optical frontend with a new electro-optical modulator (EOM), which has a corresponding bandwidth, is required for such a new BAM.

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ARRIVAL TIME MEASUREMENT

The electro-magnetic f eld of an electron bunch passing the pickup induces a short bipolar RF signal in each of the four pickup electrodes [10]. The RF signals of opposite pickup electrodes are combined. One of these combined signal will be used as a highly sensitive channel for low bunch charges. The other combined signal will be used as a channel for high bunch charges which basically operates like the low bunch charge channel but using components with lower bandwidth. Each of the combined RF signals is directed to an EOM, which additionally receives a laser pulse from the synchronization system. By setting the EOM to a modulation of 50 % of the modulation range by using a DC bias voltage U_{bias} an optimized determination of the timing difference between the RF and the laser pulse at the EOM is feasible. The laser pulse from the synchronization system has a duration of approximately 200 fs and is much shorter than the RF signal pulse from the pickup. Herefrom, with an average power of 5 mW and a repetition rate of 216.67 MHz, the peak power is about 100 W. With a correct timing of the electron bunch, the zero-crossing of the RF signal of the pickup reaches the EOM at the same time as the reference laser pulse and thus the output of the EOM is not modulated. When the electron bunch reaches the EOM with a timing offset the pickup signal shows a non-zero voltage at the RF input and therefore the amplitude of the laser pulse is modulated (see Fig. 1). The amplitude of the laser pulse is detected by a photodiode and digitized by a fast ADC. According to [10], the optical modulation M_{signal} which is imprinted onto the laser pulse of the synchronization system by the EOM can be described as:

$$M_{\text{signal}} = (1 - r) + r\left(\frac{1}{2} + \frac{1}{2}\cos\left(-\delta_0 + \frac{\pi U_{\text{bias}}}{U_{\pi,\text{bias}}} + \frac{\pi U_{\text{RF}}(t)}{U_{\pi,\text{RF}}}\right)\right) \quad (1)$$

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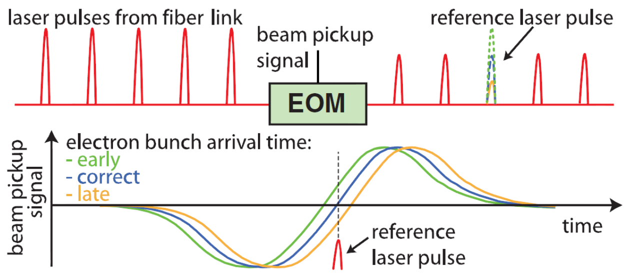

Figure 1: Principle of the arrival time measurement. The laser pulses are modulated by the EOM which is driven by the RF signal from the pickup. Arrival time deviations of the electron bunch cause different modulation voltages at the laser pulse arrival time [9].

The device specif c intrinsic operation point is presented by δ_0. $U_{\pi,\text{bias}}$ and $U_{\pi,\text{RF}}$ are the voltages to change the optical output power of the EOM from minimum to maximum at the bias port respectively the RF port. The operation point of the EOM is set by the U_{bias}. U_{RF} represents the RF signal from the pickup. The EOM parameter r presents the optical modulation depth. The base modulation without a RF signal will be set with the bias voltage to:

$$\begin{aligned} M_{\text{base}} &= (1-r) + r\left(\frac{1}{2} + \frac{1}{2}\cos\left(-\delta_0 + \frac{\pi U_{\text{bias}}}{U_{\pi,\text{bias}}}\right)\right) \\ &\underset{\text{set to}}{\approx} (1-r) + \frac{1}{2}r \end{aligned} \tag{2}$$

The real modulation M is calculated by:

$$M = M_{\text{signal}} - M_{\text{base}} \approx r\frac{1}{2}\sin\left(\frac{\pi U_{\text{RF}}(t)}{U_{\pi,\text{RF}}}\right) \tag{3}$$

The slope (S) of the RF signal of the pickup can be approximated as linear in a small time interval around the zero-crossing:

$$\begin{aligned} &U_{\text{RF}}(t) \approx S t_{\text{shift to reference}} \\ &\qquad \text{with } t_{\text{shift to reference}} \ll \text{RF pulse duration} \end{aligned} \tag{4}$$

By using a calibration constant K with

$$K = \frac{\pi S}{2U_{\pi,\text{RF}}} \tag{5}$$

the time shift between the reference laser signal and the arrival time of the electron bunches can be calculated to:

$$t_{\text{shift to reference}} = \frac{\arcsin(\frac{2M}{r})}{2K} \underset{\text{Taylor}}{\approx} \frac{M}{Kr} + \frac{2M^3}{3Kr^3} + \cdots \tag{6}$$

The accuracy of the time measurement is inf uenced by the error of the optical modulation ΔM. Using the f rst term of the Taylor series from equation (6) the accuracy of the time measurement is estimated to:

$$\Delta t \approx \frac{\Delta M}{Kr} = \frac{2U_{\pi,\text{RF}}}{\pi S r}\Delta M \tag{7}$$

Therefore, the criteria for the EOM are a low $U_{\pi,\text{RF}}$ and a high modulation depth r. A modulation depth close to 100 % is reachable. S is def ned by the pickup and can not be inf uenced by the EOM.

MEASUREMENT OF DIFFERENT EOM CANDIDATES

The commercially available EOMs are mostly produced for telecommunication and designed with an RF bandwidth with several 10 GHz. In contrast to the applications in telecommunication, the BAM system uses a pulsed laser and therefore the EOM candidates must be tested for their suitability. Three types of EOMs with different active optical materials have been characterized (see Table 1).

Table 1: List of Tested EOM Candidates for the new BAM System

EOM No.	manufacturer model	bandwidth	active optical material
1	PHOTLINE MXDO-LN-20	$\geq$ 18 GHz	$LiNbO_3$
2	COGO optronics 40G MZM	$\geq$ 33 GHz	InP
3	GIGOPTIX LX8401	$\approx$ 30 GHz	polymer

The EOM No. 1 has a bandwidth of 18 GHz only and does not reach the desired bandwidth of 30-40 GHz. However, the manufacturer offers a further type with a bandwidth of 30 GHz with otherwise similar characteristics. The test setup to characterize the EOM properties uses a pulsed laser which is similar to the one in the synchronization system. The optical power can be set by rotating a lambda-half-waveplate and a polarizing beam splitter. The RF port of the EOM was connected to a DC voltage source and the optical output power has been measured with a powermeter or with a spectrum analyzer (see Fig. 2).

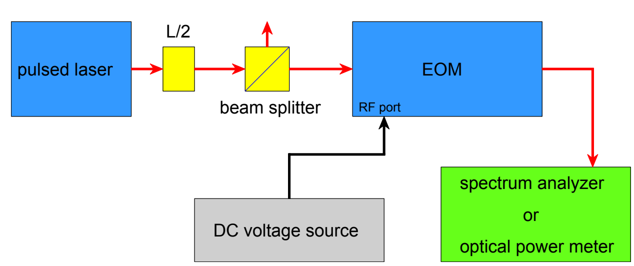

Figure 2: Schematic test setup used to characterize the EOM No. 1 and No. 2.

The results from the EOM No. 1 have been carried out without a voltage source at the bias port. The optical output power in dependence of the voltage at the RF port is shown in Fig. 3. Based on the measured data the modulation depth r is determined with (96.4 ± 0.1) % and the

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value of $U_{\pi,\mathrm{RF}}$ is calculated as (5.4 ± 0.4) V. The insertion loss was measured with 4.7 ± 0.2 dB.

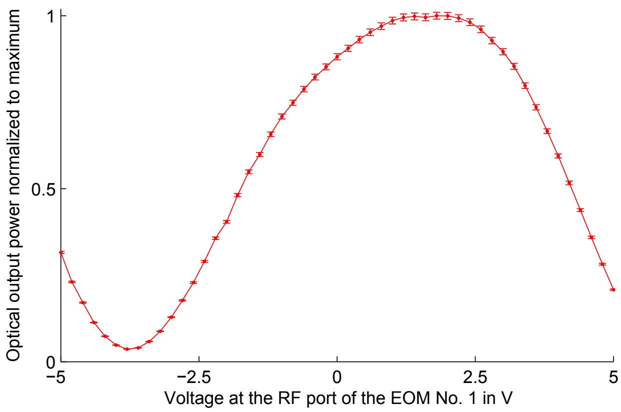

Figure 3: Measured optical output power of EOM No. 1 in dependence of the voltage at the RF port. Based on these data the values of $U_{\pi,\mathrm{HF}}$ and r can be calculated.

The control of EOM No. 2 is more complex because the active optical material is also an electronic semiconductor. This EOM has two bias ports, one for each interferometer branch which operate complementary. The bias ports of the EOM operate only with positive voltage. Furthermore, this EOM has an additional port at the substrate backplane. A voltage at the backplane port reduces $U_{\pi,\mathrm{RF}}$. The measurement of the EOM No. 2 was carried out with different voltage settings at the backplane port and different voltage settings at the bias ports. The results with zero Volts at both bias ports are shown in Fig. 4.

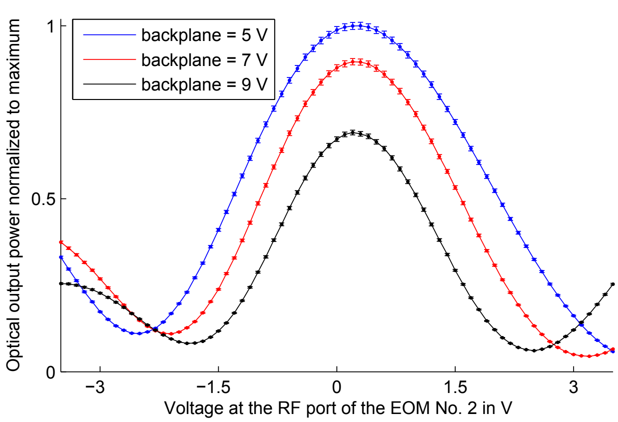

Figure 4: Measured optical output power from EOM No. 2 in dependence of the voltage at the RF port with different backplane voltage settings. Based on these data the values of $U_{\pi,\mathrm{HF}}$ and r can be calculated.

The optical transmission in dependence of the voltage is not symmetric and furthermore the minima and maxima of the optical transmission in dependence of the voltage at the RF port are different. Thus r and $U_{\pi,\mathrm{RF}}$ had to be calculated separately for negative and positive voltages at the RF port (see table 2). The insertion loss increases also with the voltage at the backplane. With a backplane voltage of 5 V the insertion loss with the pulsed laser was measured with 19.1 ± 0.2 dB. For comparison the insertion loss was also measured with a cw laser at 10 mW power with 9 dB. This means this type of EOM is not useable for the BAM system which used pulsed laser from the synchronization system.

Table 2: Results for EOM No. 2 with Zero Volts at the Bias Ports

voltage at backplane port		transmission minimum in voltage area neg.	pos.
5 V	r	(88.9 ± 0.3) %	≥ 94.18 %
	U_p	(2.8 ± 0.1) V	≥ 3.2 V
7 V	r	(87.8 ± 0.3) %	(94.9 ± 0.2) %
	U_p	(2.3 ± 0.1) V	(2.9 ± 0.1) V
9 V	r	(88.1 ± 0.3) %	(91.2 ± 0.2) %
	U_p	(2.1 ± 0.1) V	(2.3 ± 0.1) V

The EOM No. 3 indicates a high-pass characteristics and a DC voltage source at the RF port show nearly no change in the optical modulation. Thus a new test setup was build to measure the properties of the EOM. In the new test setup the DC voltage is replaced by a 1.3 GHz voltage source with a temporal correlation to the pulsed laser source (see Fig. 5).

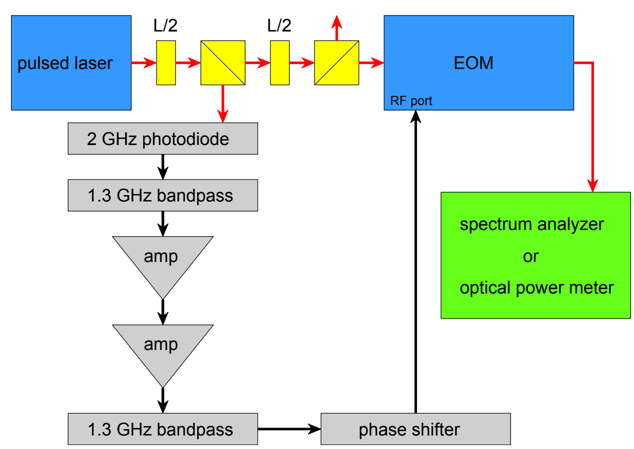

Figure 5: Schematic test setup for the measurement of EOM No. 3.

In this setup, a part of the laser pulse is applied to a photo detector with a bandwidth of 2 GHz which produces a frequency comb with harmonics of the repetition rate of the laser source. By using a 1.3 GHz bandpass filter with a bandwidth of 50 MHz the sixth harmonic was filtered and amplified afterwards. The second bandpass filter suppressed potential distortions of the amplifiers. By using a phase shifter the timing between the laser pulse and the electrical 1.3 GHz signal can be shifted (see Fig. 6).

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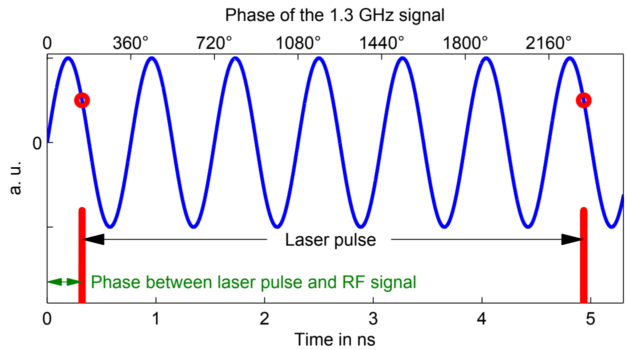

Figure 6: 1.3 GHz voltage signal which has been connected to the EOM No. 3 (blue). The instantaneous voltage during the pass of the laser pulse through the EOM can be approximately regarded as constant (red dots). By using the phase shifter the timing between laser pulse and RF signal (green arrow) can be shifted and therefore the instantaneous voltage can be changed.

The voltage during the pass of the laser pulse through the EOM in dependence of the phase α of the phase shifter can be described with:

$$U(\alpha) = U_0 \sin(\alpha + \delta_e) \tag{8}$$

With U_0 the amplitude of the 1.3 GHz signal and δ_e the intrinsic electrical phase offset of the test setup. The results of the measurement with U_0 = 3.5 V are shown in Fig. 7. Based on the measurement data a f t was conducted by using equation 1 with a linear scaling and replacing $U_{\mathrm{RF}}(t)$ with equation 8. The free f t parameters are the linear scaling factors, δ_e, δ_0, r and the value of $U_{\pi,\mathrm{RF}}$. The bias port of the EOM was not connected to a source at this measurement. The results of the f t provide a $U_{\pi,\mathrm{RF}}$ = 2.97 V $\pm$ 0.02 V and a r = 95.0 % $\pm$ 1.3 %. The insertion loss with an averaged optical input power of 5 mW from pulsed laser was measured with 8.7 $\pm$ 0.2 dB.

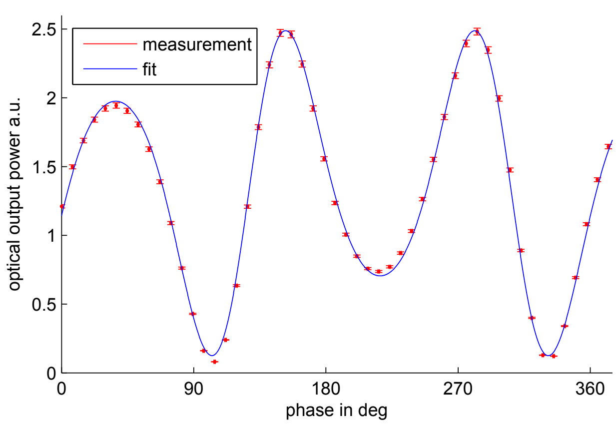

Figure 7: Optical transmission of the EOM No. 3 in dependence of the phase of the phase shifter.

CONCLUSIONS AND OUTLOOK

A high measurement accuracy of the BAM system requires a low $U_{\pi,\mathrm{RF}}$ and a high modulation depth of the EOM. The EOM No. 1 with $U_{\pi,\mathrm{RF}}$ = 5.4 V is very high compared to the two other EOMs. However, this EOM will likely be used in the high charge channel of the BAM system [6].

The EOM No. 2 has an adjustable $U_{\pi,\mathrm{RF}}$ which can be set to a value below than 2.3 V by using a backplane voltage. However, this EOM has a problem with a pulsed laser. By using a pulsed laser with a peak power in the order of 100 W, the insertion loss increases drastically. For the application in the BAM system, the insertion loss must be lower than 10 dB and therefore this EOM is not suitable.

The EOM No. 3 with a $U_{\pi,\mathrm{RF}}$ lower than 3 V and a modulation depth higher than 93 % is the most suitable candidate. The insertion loss is higher compared to EOMs based on $\mathrm{LiNbO_3}$ which have been used in the currently BAM system. However, the optical output power is suff cient by using an averaged optical input power between 5 mW and 10 mW which corresponds to a peak power up to 200 W. The next step is to install this type of EOM in the new electro-optical front end of the BAM system.

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