16th International Particle Accelerator Conference,Taipei, Taiwan JACoW Publishing
ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-THPS107

SUBSTRATE MATERIAL STUDIES FOR PCB-BASED ELECTRO-OPTICAL BUNCH ARRIVAL-TIME MONITORS FOR XFELs

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Abstract

The all-optical synchronization system used in several X-ray free-electron laser facilities (XFELs) relies on electro-optical bunch arrival-time monitors (EO-BAM) for measurement of the arrival time of single bunches in regard to an optical reference. An upgrade of the established EO-BAM is intended to achieve a sensitivity that enables stable operation of XFELs with bunches down to a minimum charge of 1 pC, or to significantly increase the resolution in normal operation above 20 pC. It requires a fundamental redesign of the rf path including pickups and electro-optical modulators. The novel concept of the pickup structure comprises planar pickups with a bandwidth of up to 100 GHz on a printed circuit board (PCB) with integrated combination network. The theoretical jitter charge product of the concept has been estimated by simulation and modelling to be in the order of 9 fs pC and the concept was proven experimentally with a 67-GHz demonstrator at the ELBE facility at HZDR. In this contribution, we compare ceramic and glass substrates in terms of radiation hardness, sensitivity, and manufacturing capabilities. Different fabrication technologies result in varying tolerances, which influence the achievable sensitivity. Additionally, material losses significantly impact the achievable bandwidth.

INTRODUCTION

In recent years, a concept for an improved electro-optical bunch arrival-time monitor (EO-BAM) has been proposed. The design aims for an increased sensitivity in order to enable stable operation of X-ray free-electron laser facilities (XFELs) with bunch charges of 1 pC or below and to path the way for low-charge applications like MeV ultra-fast electron diffraction (UED) [1]. It could also significantly increase the resolution in normal operation, provided that the risk of overvoltage has been properly addressed.

For an early version of the new concept, a theoretical jitter charge product has been estimated by simulation and modelling to be in the order of 9 fs pC [2], thus allowing pC operation with single-digit fs resolution. A 67-GHz demonstrator with commercially available substrates was realized as an intermediate step to prove the viability experimentally at the ELBE accelerator at HZDR [3].

In the following section, the optical synchronization and more specifically the EO-BAM are briefly described, before considerations on suited substrate materials for the novel pickups structure are presented.

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OPTICAL SYNCHRONIZATION

Some of the large scale XFEL facilities, as the European XFEL and ELBE, utilize an all-optical synchronization system, where a comb of laser pulses in a phase-locked loop with the main rf oscillator is used as a timing reference [4]. The optical reference is distributed via actively length-stabilized fibers of up to a few km length along the linear accelerator and to the experimental hall [4, 5]. The timing reference is used in different substations. One example are the laser-to-rf modules used for resynchronization of the phase of the main rf, which is distributed through conventional coaxial cables that are susceptible to changes in the ambient temperature [5]. By laser-to-laser synchronization the injection laser as well as the experimental lasers used in time-critical pump-probe experiments can be locked to the timing reference in a different set of end stations [5]. Furthermore, the optical reference is used in the beam diagnostics and specifically the EO-BAM [5].

Electro-optical Bunch Arrival-time Monitors

The EO-BAM measures the single-bunch arrival time relative to an optical reference pulse. It comprises a pickup structure, an electro-optical modulator (EOM) and the data acquisition electronics (DAQ). In operational EO-BAMs, the pickup structure uses pairs of high-bandwidth cone-shaped button-like pickups [6, 7]. The combination of two opposed pickups increases the signal strength and also reduces the susceptibility to beam misalignment [7]. The transient rf signal induced in those pickups is sampled by the optical timing reference in the EOM [4]. By an adjustable delay stage a perfect overlap of the signal's zero crossing with the reference pulse is set [8]. The arrival-time jitter of the electron bunch leads to a mismatch between reference and rf signal, which in the EOM is imprinted on the intensity of the optical reference [4]. This intensity modulation is measured in the DAQ to retrieve information about the arrival-time deviation [4, 8, 9].

BAM Upgrade

The envisioned upgrade of the BAM affects the EOM as well as the pickup structure. The later will be based on a printed circuit board (PCB) with planar pickups, integrated combination network and high bandwidth vacuum

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feedthrough as realized in a first demonstrator [3]. The final prototype aims for a ten-fold increase in the slew rate at the zero crossing of the rf signal, which is a major factor for the achievable BAM resolution. The following section gives general considerations on the substrate choice for the demonstrator and future prototypes.

SUBSTRATE SELECTION

The insulator material used for the PCB has to be chosen carefully, and many factors have to be taken into account. The most important criteria are summarized as follows

- Signal performance
- Ultra-high vacuum (UHV) suitability
- Radiation hardness
- Manufacturing capabilities and tolerances
- Mechanical soundness

Ideally the substrate must be low maintenance while being mounted in the beamline for extensive times without spoiling the vacuum or wearing down from radiation. Therefore, radiation hardness and low outgassing are important traits of the material. But mechanical properties should not be neglected either. Ultimately, signal quality is the most important factor. To narrow down the selection in the following, some general considerations are made.

Radiation and Vacuum Requirements

Radiation effects on the substrate's metallization are a minor concern, since only large doses of neutrons and other high-energy particles are expected to cause mild to severe damage [10]. Similarly, ceramics are highly resistant to radiation, but formation of gas pockets and of f-centers may have a negative effect above 10^8 Gy [10]. Polymers are particularly susceptible to radiation, specifically, long-term radiation with low dose-rates causes relatively high mechanical degradation [10]. Typical PCB materials, like different FR4 (glass-reinforced epoxy laminates) samples, as well as Rogers RO4003C and RO4350B (both glass-reinforced hydrocarbon/ceramics [11]), showed swelling and as a consequence a slight change in permittivity after gamma and neutron radiation [12]. For fused silica no changes of the optical properties were found under proton irradiation [13]. Though these studies cannot be generalized, they indicate, that radiation has only a minor role in the case of XFEL facilities with low charge beams.

Gold or silver as well as oxygen free copper are suited for UHV applications [14]. If soldering is inevitable, indium is a good candidate with low melting point and acceptable vapor pressure [14]. Glass is also well suited for UHV especially for windows and as insulator [14]. Additionally, ceramics, e.g., with high alumina content or glass-ceramics like Macor®, can be used in UHV as an insulator [14]. Polymers are usually not suited for UHV, since organic materials tend to have a significantly higher outgassing rate [15], though some elastomers are used for HV gaskets [14].

Following these generalized statements, ceramics and glass are possible insulator materials, while polymers are more likely to be ruled out.

Mechanical Aspects

Ceramics and glasses are brittle and therefore difficult to machine. It may be necessary to tamper a glass substrate after cutting it into the desired form, however this will increase the risk of cracks when inserting the material because of the increased sensitivity of the outer edge [16]. A larger margin should be provided. Generally, glass has disadvantages in processing, but is more suitable for the intended use in vacuum and radiation. Since it is not a mass-produced part the difficulties in production could be tolerable.

Electrical Performance

For good signal transmission a low loss factor even at high frequencies is needed. Upper limits for the frequencies of operation are necessary to prevent leakage into the substrate or higher order modes forming at the strip. Approximate formulas can be found in [17]. To increase cutoff frequencies, it is favorable to decrease relative permittivity ϵ_r and/or thickness of the substrate. Additionally, transverse resonances can occur for very wide strips. The low dielectric constant would also reduce the dielectric losses and increase the phase velocity, which is beneficial for temporal separation of the signal and upstream wakefields.

DEMONSTRATOR

For the demonstrator, production risks had to be minimized in order to meet the deadlines for measurements and to allow for last minute adaptions in the ongoing development. Therefore, the decision was made to use a ceramic substrate instead of a glass substrate, since many ceramic substrates can be machined with conventional milling machines with precision in the order of a few tens of μm.

The short-term vacuum suitability has been tested with a batch of four different 20 mm × 40 mm Rogers substrate samples at once. Based on availability these were the hydrocarbon ceramic RO4003C, as well as the ceramic, hydrocarbon, thermoset polymer composites TMM® 3, 4 and 10i of various thicknesses between 0.38 mm to 0.51 mm. The vendor recommended RO4730G3 in terms of radiation hardness, but no sample was available due to the tight schedule. For the vacuum test most of the top metallization (copper) was removed with a milling machine to get a realistic surface condition. The cleared surface was a total of 32 cm^2 on top and about 2.3 cm^2 lateral surface neglecting thin traces. The test showed that baking the samples at 105 °C for almost three days was necessary to reach a sufficiently low pressure of 7×10^{-9} mbar [3]. Due to the hydrocarbon content, further testing is recommended before longer operation, but these tests were omitted for the demonstrator, since for a final design a glass substrate is preferred performance wise.

For the final decision a 50 Ω geometry for each of the available substrate was found by field simulations of a piece

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of microstrip line with the Wakefield Solver of CST Particle Studio®, followed by a first selection based on the approximately calculated cutoff frequencies. For the best candidates a full model was implemented in the simulations. These investigations were not conclusive, as the parameter space is far too big and only a few examples could be examined in the limited time. Finally, a TMM® 10i substrate was used for the demonstrator.

Preliminary Damage Assessment

As reported in [3, 18] the demonstrator test showed that the PCB-based pickup structure is feasible and in line with simulations. In this contribution we inspect its PCB for damages occurring during deployment. After the demonstrator was inserted in the THz-beamline of ELBE from Juli 2023 to September 2024, the substrate was exchanged. It had been exposed for more than one year of regular operation. The beam time is divided between different beamlines depending on the users and not always passing the demonstrator. No information about the actual exposure is available, but some cases of beam incident on the substrate were reported.

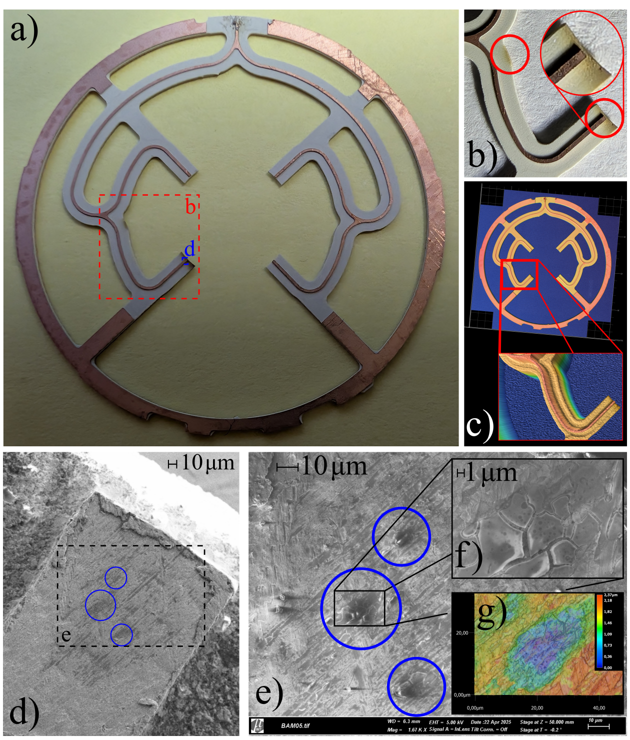

Figure 1: Rogers TMM® 10i Substrate after about 1 year of operation (a) and zoom on discolored spots (b). Additionally, the damages were reviewed in an 3D optical profilometer (c), a SEM image (d) to (f) and an optical microscope (g). Locations and scales are indicative.

Beam impacts are the suspected cause of the dark discoloration on the substrate visible in Fig. 1(b). A profilometer image (c) does not show larger anomalies apart from residual solder at the connector side. The scanning electron microscope (SEM) images (d) to (f) showed a few distinct features, which mostly were non-conducting particles probably from contamination after decommissioning. Three anomalies (blue circles) with an extension in the range of 10 µm were located close to the discolored arm and not observed on other parts of the copper trace. The optical microscope (g) indicates that the largest spot is recessed by about 1 µm to 2.4 µm (green to red color scale). These damages may have already occurred during the manufacturing process, but it could also be a consequence of local heat dissipation from the electron beam impacting from the back.

Neither analysis indicated a risk of structural failures or loss of the electrical connection, but a change of dielectric properties and disturbances of electric surface currents cannot be ruled out either. The risk of the beam impacting on the substrate should be minimized.

CONCLUSION

In this contribution, substrate material studies were carried out for PCB-based electro-optic beam arrival-time monitoring. We demonstrated the feasibility of ceramics for rapid prototyping via rf milling systems and observed beam-induced damages of the PCB localized to directly impacted regions. While initial assessments suggest potential compatibility with vacuum and radiation environments, long-term material stability under these conditions requires further investigation. Glass substrates, particularly fused silica with gold cladding, exhibit promising signal performance for the EO-BAM, despite challenges in mechanical processing. Laser milling and etching techniques show potential to overcome fragility issues inherent in glass wafer fabrication. However, alternative materials are still an option and should also be investigated.

Critical unresolved challenges include the influence of vibrations, originating from vacuum pumps or the beam itself, on measurement accuracy, and the mitigation of timing inaccuracies caused by positioning errors. Unless mitigated by temporal averaging, a positioning error of 1 µm may introduce arrival-time inaccuracies exceeding 3 fs when asynchronous with the beam. Proposed strategies to address these limitations include resonance avoidance through eigenfrequency tuning and substrate reinforcement.

While ceramics and fused silica substrates offer viable pathways for EO-BAM applications, future work must prioritize vibration isolation, precision alignment protocols, and extended radiation exposure testing to ensure robust operational performance in accelerator environments.

ACKNOWLEDGEMENTS

This work is supported by the German Federal Ministry of Education and Research (BMBF) under contract No. 05K22RO2. We would like to thank Manuel Heilmann from GSI and Stephan Klaproth from THM, as well as Artem Kuzmin from KIT for providing the optical 3D profile scan respectively the microscopic images of the used ceramic substrate.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-THPS107

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