

# DESIGN AND INTEGRATION OF THE OPTICAL REFERENCE MODULE AT 1.3 GHz FOR FLASH AND THE EUROPEAN XFEL

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## Abstract

In this paper we present recent progress on the integration and implementation of the OPTical REFerence Module (REFM-OPT) for the free-electron lasers FLASH and the European XFEL. In order to achieve high energy stability and low arrival time jitter of the electron beam, the accelerator requires an accurate Low-Level RF (LLRF) field regulation and a sophisticated synchronization scheme for various devices along the facility. The REFM-OPT is a 19" module which is responsible for resynchronizing the 1.3 GHz reference signal for the LLRF distributed by coaxial cables to a phase-stable signal of the optical synchronization system. The module provides a 1.3 GHz output signal with low phase noise and high long-term stability. Several sub-components of the REFM-OPT designed specifically for this module are described in detail. The readout electronics of the high-precision Laser-to-RF (L2RF) phase detector are presented as well as the integration of this key component into the 19" module. Additionally, we focus on design solutions which assure phase stability and synchronization of the 1.3 GHz signal at several high power outputs of the module.

## INTRODUCTION

For the European XFEL, the optical synchronization system has become an invaluable support for the 1.3 GHz coaxial cable based timing distribution. High phase stability requirements [1] have made the design of the RF-based reference system a challenging task. By using phase-stabilized fiber links [2] it is possible to deliver highly stable optical signals to the locations of different LLRF stations without being affected by losses and drifts arising in RF cables over the huge distance of the main linac.

The hereby presented REFM-OPT is an interface between the reference signal from the optical synchronization system and the RF system directly supplying the LLRF stations [1]. It allows to resynchronize the RF reference at these locations to the laser reference on a femtosecond level.

The REFM-OPT comprises a number of electrical units supporting the L2RF phase detector, for which we showed till now unmatched stability of 3.6 fs peak-to-peak over 24 hours for a 1.3 GHz signal [3].

The REFM-OPT is capable of supplying different modules of the LLRF system, which require both, phase stable input and a high power level of 21 dBm (Fig. 1). For the European XFEL the module is combined with other reference

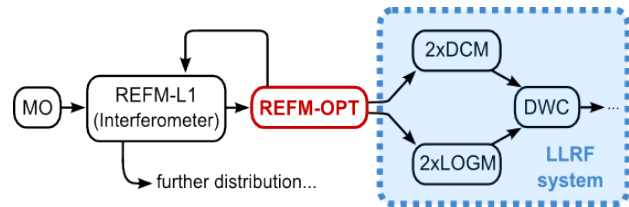


Figure 1: REFM-OPT connection scheme for the first linac station (L1) of the European XFEL. Master Oscillator (MO), REference Module (REFM), Drift Calibration Module (DCM), LO Generation Module (LOGM), Down Converter (DWC).

modules REFM (pure RF-based interferometers [1]). The engineered REFM-OPT version built for tests at FLASH provides 4 outputs and will work as a stand alone unit, because an interferometer system was not foreseen and is not necessary for the much shorter accelerator facility FLASH.

## LASER-TO-RF PHASE DETECTOR

The L2RF phase detector consists of an electrical and an optical part, in which the crucial element is a fiber-coupled electro-optical modulator (EOM). In this EOM 200 fs long laser pulses sample the instantaneous RF signal amplitude. Because of the special frequency relation between the two, in the ideal case, i.e. no phase mismatch, the optical pulses meet the RF at zero-crossings, which causes no error signal to be generated at the optical output. The RF output of the EOM provides then a signal perfectly in phase with the laser reference. In the opposite case the RF introduces a laser pulse modulation, which is later detected and amplified by the L2RF electronics. By a special arrangement of the optical delay lines around the EOM, it is possible to distinguish three error signals, which are RF phase drift, EOM bias drift and drift of the first delay line in the optical setup. They are converted to the electrical domain by a photodiode and differentiated in the L2RF electronics.

### L2RF Electronics

The L2RF printed circuit board (L2RF PCB, Fig. 2) was described in detail in [3]. It implements the detection of all 3 error signals. It is designed to fit into a 10 cm x 20 cm housing. All the connectors are placed on the long side, because the space available for the electronics in the 3 HU 19" REFM-OPT housing is very limited and this solution requires access to the PCB only from one side. Besides panel mounted photodiodes and SMA connectors, there is

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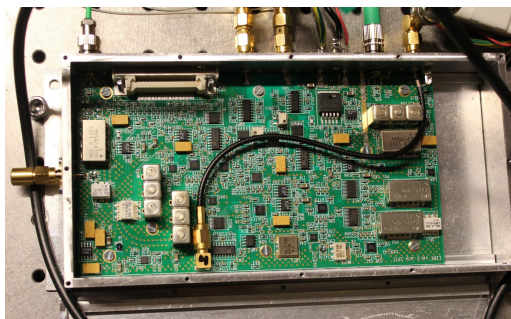


Figure 2: L2RF readout electronics.

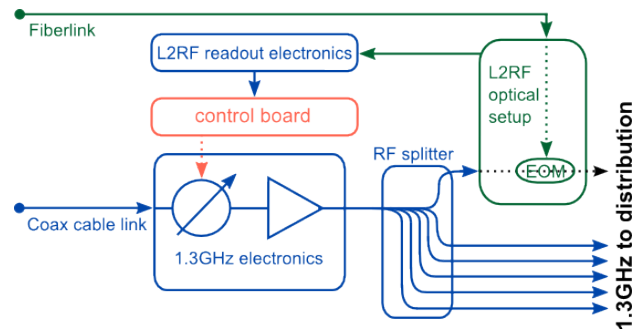


Figure 4: REFM-OPT block diagram.

an MDR<sup>1</sup> connector to the controller board (TMCB), which allows to maintain good thermal isolation of the housed PCB. This connection is an interface to operate on-board attenuators and phase shifters necessary for L2RF phase detector calibration and operation. Additionally it is possible to set the error signal amplification and bandwidth of the detector, which is derived from the control loop bandwidth of a superconducting cavity (40kHz, e.g. in [5]). Therefore the overall noise (detection limit) for the L2RF electronics has been calculated within 1 Hz-100 kHz. In this bandwidth (and at error amplification by a factor of 50) it accumulates to less than 1 fs.

### REFM-OPT 1.3 GHz ELECTRONICS

The 1.3 GHz electronics (see the scheme in Fig. 3) implements phase error correction to the 1.3 GHz RF. An input signal comes either from the REFM (Fig. 1) or directly from the coaxial cable RF reference distribution system originating from the master oscillator. A remote controllable attenuator together with some power margin foreseen in the design allow to compensate for 3 dB power undervaluation. An isolator preserves any back-reflection, which might otherwise pollute the preceding installations. The phase mismatch correction is carried out by a passive vector modulator. The PCB has on-board PT1000 sensors and power detectors for the monitoring purpose, which can later also be used for example for an RF power feedback.

The board was designed to fit into the same housing like the L2RF electronics, whereas all the connectors are placed on the short walls. This realization enables to pile both

PCBs and to have an easy access to all connections. It also corresponds to the natural REFM-OPT interfaces, where the input is placed in the rear, and the output on the front with respect to the 19" box.

The additive phase noise measured for the PCB is in the level of 1.5 fs (integrated in the frequency range from 10 Hz to 100 kHz).

### OUTPUT SPLITTER DRIFT

In order to supply several different modules, the REFM-OPT has to split the low-drift output signal without losing its performance. The straightforward realization would be to put the splitter behind the RF output of the EOM. Unfortunately, this introduces an additional component outside the control loop, i.e. no longer stabilized. Instead we developed the solution depicted in Fig. 4, in which the overall and simplified REFM-OPT layout is presented. It is based on the measurement result presented in the next section, which shows, that the relative drift between splitter outputs is much lower than in between its input and output. Here, we stabilize one of the outputs inside the loop, which gives one drift-free output like without splitting, available to the most drift-sensitive module. The other customers suffer only from the low relative drift between the stabilized and non-stabilized output.

### Drift Measurement

The measurement setup is shown in Fig. 5. The device under test is a 2-way MECA 802-4-3.100-M02 splitter, which is a Wilkinson, special teflon free design. A similar splitter, but a 6-way version, is planned for the REFM-OPT for the European XFEL.

<sup>1</sup> <http://solutions.3m.com>

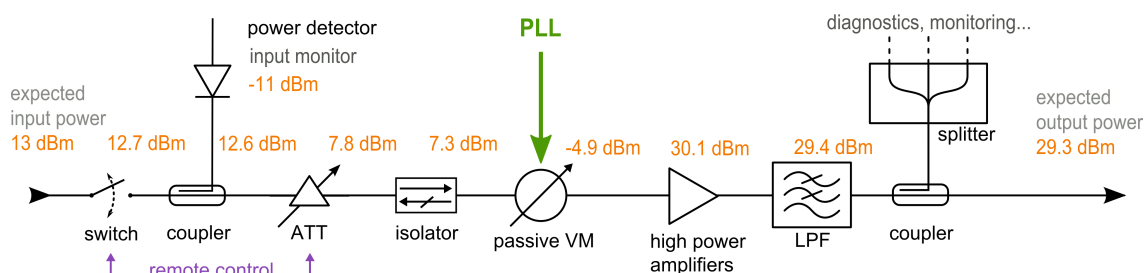


Figure 3: Simplified scheme of the 1.3 GHz electronics.

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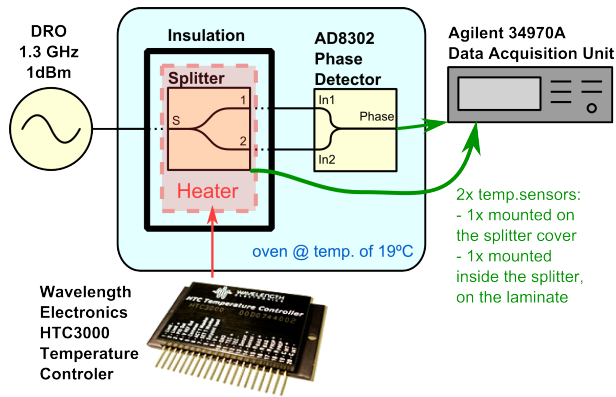


Figure 5: Layout of the splitter drift measurement setup.

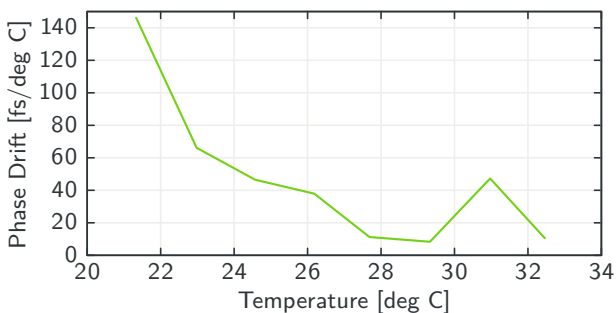


Figure 6: Drift between the outputs of the 2-way MECA 802-4-3.100-M02 splitter.

The phase detector and crucial connections are placed together with the tested splitter in a temperature stabilized environment, which reduces their influence on the measured drift. The splitter was warmed over by a heating resistor in the insulating housing. The measurement was performed for several temperature steps (each step of approximately 2°C and lasting 2 hours) from around 20°C to 33°C. From this the drift between the outputs per degree Celsius was derived (Fig. 6). It can be noticed, that the lowest drift coefficient for the measured splitter is around 29°C, which corresponds to the estimated module temperature in the tunnel.

## REFM-OPT MODULE INTEGRATION

All the above mentioned elements have been integrated into one 3 HU 19" housing as shown in Fig. 7. Remaining parts include:

- digital controller board (TMCB), which will implement all the control loops and reading all the sensors
- Fuse-Relay board (FRED), which provides all the power supplies and their remote management
- temperature controller necessary to stabilize the L2RF optical setup
- Amplitude Monitor (AM), which allows to monitor the optical power necessary for the L2RF optics operation

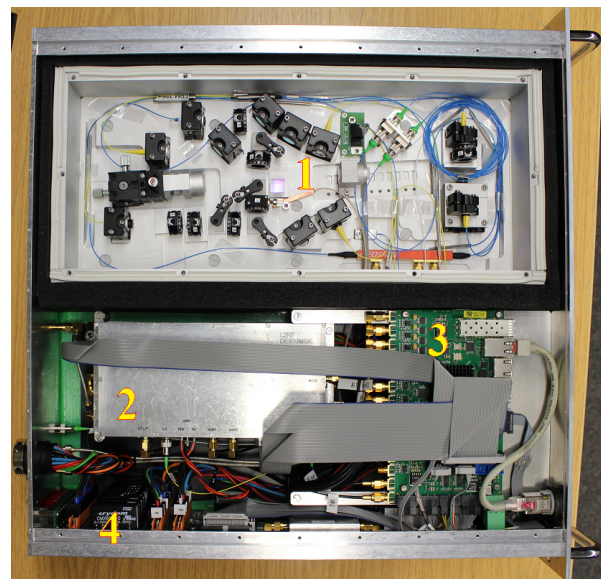


Figure 7: Top view of the assembled module. (1) L2RF optics, (2) a pile of PCBs: 1.3 GHz and L2RF electronics, (3) TMCB and below: splitter, temp. controller, AM, (4) FRED mounted on the side wall.

## SUMMARY AND OUTLOOK

All the necessary hardware for the REFM-OPT at FLASH has been designed, tested and integrated into the final housing. Regarding upcoming installations for the European XFEL, some supplemental measurements, especially for the 4-way and 6-way power splitters, are necessary. In case of suboptimal environmental conditions, a temperature control for the splitter might be implemented. For the 1.3 GHz electronics, alternative phase control solution, promising even lower additive phase noise, is in preparation.

Two assembled prototypes will be tested with the newly developed firmware in the near future and later be installed at FLASH.

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