

HIGH-PRECISION LASER MASTER OSCILLATORS FOR OPTICAL TIMING DISTRIBUTION SYSTEMS IN FUTURE LIGHT SOURCES

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Abstract

An ultra-stable timing and synchronization system for linac-driven FELs has been designed providing 10 fs precision over distances of several kilometers. Mode-locked fiber lasers serve as master oscillators. The optical pulse train is distributed through length-stabilized fiber links. The layout of the optical synchronization system and its phase noise properties are described. A prototype system has been tested in an accelerator environment and has achieved the required stability.

INTRODUCTION

One of the key challenges for X-ray free electron lasers is to implement an RF timing and synchronization system with an accuracy in the order of 10 femtoseconds that allows to fully exploit the narrow width of the X-ray pulses for time-resolved experiments. An electron beam timing jitter of 10 fs translates into very small tolerances on the amplitude and phase stability of the RF in the accelerating cavities of 10^{-4} and 0.01 deg, respectively. In case of the XFEL, such an ultrastable reference frequency with lower phase jitter than the X-ray pulse width has to be distributed over a distance of several kilometers.

These demanding requirements cannot be met by conventional RF distribution systems based on microwave oscillators and semi-rigid coaxial cables. A promising alternative is an optical system, depicted schematically in Figure 1 [1]. A periodic train of sub-picosecond light pulses is generated in a mode-locked fiber laser and distributed along the linac through fibers with optical length stabilization. The synchronization information is contained in the precise repetition frequency of the pulse train. At the remote locations, low-level RF signals are generated by using a photodiode and a bandpass filter to pick the desired harmonic of the laser repetition rate, or by phase locking an RF source to a harmonic of the pulse train [2].

MODE-LOCKED FIBER LASERS

Mode-locked fiber lasers are well suited to realize an optical master oscillator, because of the ease of coupling to the fiber distribution system, their excellent long-term stability, and the well-developed and mature components that are available at the optical communications wavelength of 1550 nm. Erbium-doped fiber lasers can generate

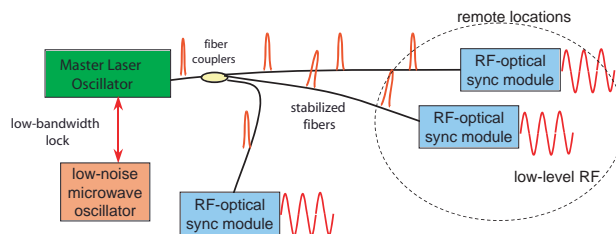


Figure 1: Schematic of the optical timing synchronization system.

pulses from picosecond down to 35 fs in duration by phase-coherent lasing of multiple longitudinal modes. A description of the mode-locking can be found elsewhere [3].

PHASE-NOISE PERFORMANCE OF MODE-LOCKED FIBER LASERS

One can divide the phase-noise spectrum into two regions of interest. Noise at high offset frequencies (typically more than 10 kHz) cannot be compensated by feedback systems, hence the laser must feature low intrinsic jitter in that frequency range. Our Er-doped fiber lasers fulfil these requirements (see Figure 2). Phase noise at lower frequencies, due to microphonics and thermal drifts, can be compensated by locking the laser to an ultra-low noise RF oscillator. This is done by using a phase-locked loop (PLL) and generating an error signal by comparing a suitable harmonic of the laser repetition rate to the RF. This signal is fed back to a fiber stretcher, onto which a part of the laser cavity fiber is wound. Thereby the laser repetition rate is adjusted. The unity gain point of the PLL has to be chosen carefully to minimize the remaining phase noise of the signal.

A 1550 nm Erbium-doped fiber laser (EDFL) has been built and its noise performance was characterized. The EDFL is a stretched-pulse laser, implementing dispersion management [4]. It produces 1 nJ pulses of ≥ 100 fs length at a repetition rate of 40 MHz. The laser output is amplified using a custom built Er-doped fiber amplifier to seed several optical fiber links. Figure 2 shows the single side-band phase noise spectrum of the harmonic at 1.3 GHz, extracted from the pulse train after photodetection and filtering. In free running condition, the integrated time jitter from 1 kHz to the Nyquist frequency of 20 MHz amounts

to 10 fs. When locked to the reference oscillator, the low-frequency phase noise of the laser is suppressed and the phase noise spectrum follows that of the reference oscillator (for frequencies < 1kHz). There is virtually no signal degradation at higher frequencies. The absolute timing jitter at low frequencies is of no major concern as long as accelerator subsystems can follow the reference with sufficient bandwidth. This is commonly the case for offset frequencies below 1 kHz. However, the relative timing jitter between different subsystems has to be kept low. Jitter added through the distribution system is thus a major issue.

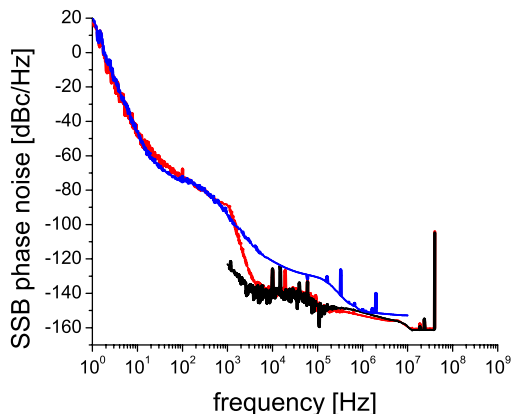


Figure 2: Spectral density of single-sideband phase noise for the free-running EDFL (black), the RF reference oscillator used to lock the EDFL (blue), and the EDFL locked to the reference (red).

MEASUREMENTS IN AN ACCELERATOR ENVIRONMENT

In order to verify that the excellent laboratory performance can be transferred to an accelerator environment, measurements were conducted at the MIT-Bates Linear Accelerator Center. A schematic of the experiment is shown in Figure 3. We utilized a previously installed 500 m-long single-mode optical fiber. The experiment consisted of three separate parts: (1) locking of the EDFL to the S-band master oscillator at the Bates Facility to reduce the close-in noise of the laser system, (2) stabilizing the optical length of the fiber with an RF-based feedback to minimize the timing jitter added by the optical transmission line, and (3) recovering an RF signal after 1 km of total fiber length with minimal added jitter. The entire experiment was conducted over a time span of three weeks. The fiber laser worked reliably during this time without loss of mode-locking or significant increase of its phase noise.

Optical fibers exhibit a temperature dependent refractive index which causes an arrival time jitter of the pulses propagating through the fiber ($\delta t/t \sim 10^{-6}/^{\circ}\text{C}$ [5]). To stabilize the fiber transit time, part of the light is reflected back at the end of the fiber. The periodic pulse train coming directly from the laser and the pulse train returning through

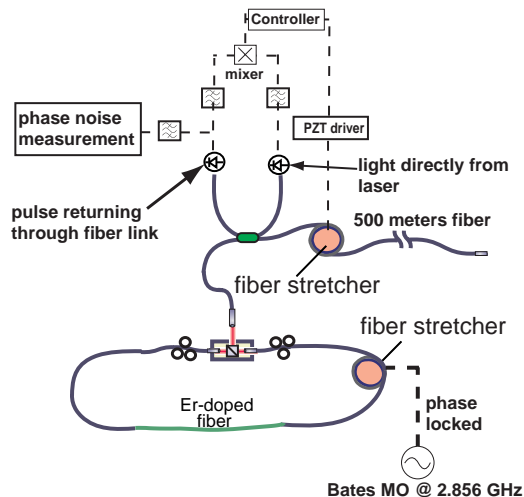


Figure 3: Schematic setup of the setup at the MIT Bates Laboratory.

the fiber are detected using two high-bandwidth photodiodes. The 1 GHz harmonics of the diode signals are combined in quadrature in a mixer. The resulting phase error signal is fed back to a piezo-controlled fiber stretcher. For a coarse lock, an RF-based scheme as described above is used while the stability can be further increased using optical cross-correlation. Thereby phase drifts in the photodiodes are eliminated.

The phase noise measured in open loop resp. closed-loop condition of the length-stabilizing feedback system is shown as an inset to Figure 4. If the loop is open, the integrated jitter in a bandwidth between 0.1 Hz and 5 kHz amounts to 66 fs. With active feedback the jitter is reduced to 12 fs.

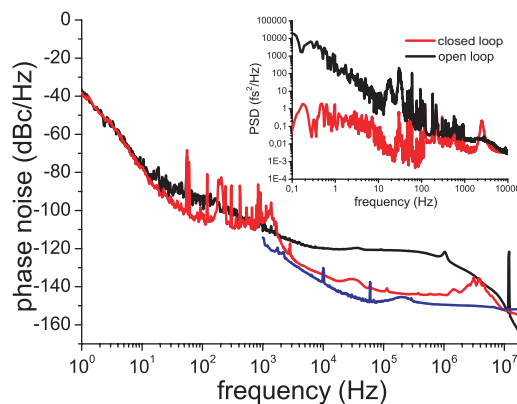


Figure 4: Single sideband phase noise of the Bates Master Oscillator (MO) (black), the EDFL locked to the reference after transmission through the link (red) and the free running EDFL (blue). Inset: Mixer output signal of the RF fiber link stabilization.

After stabilizing the fiber link (500 m-long) and locking the EDFL to the RF master oscillator, the residual phase noise of the signal at the end of the fiber link is the rele-

vant parameter. Figure 4 shows this residual phase noise in comparison to the phase noise of the RF master oscillator. It is seen that the laser follows the MO quite well in the lower frequency range except for some technical noise at multiples of 60 Hz. This is due to the pump diode power supply and could be eliminated by running the pump diodes on battery power or by better isolation of the diode driver. At an offset frequency of 1.5 kHz, the spectra of the free-running laser and the RF oscillator meet. As can be seen in Figure 4, the locked EDFL phase noise spectrum is almost identical to the free running laser spectrum inside the locking bandwidth (blue line).

RELIABILITY OF A LASER MASTER OSCILLATOR SYSTEM

A laser master oscillator (LMO) system has been designed for the FEL facility FLASH at DESY which can fulfil the uptime requirement of $> 99\%$. Although an Er-doped fiber laser, if set up correctly, will work for several weeks without loosing mode-lock, a redundancy is needed which means that the laser has to be duplicated. In case of failure of the laser in operation, the exception handling system of the linac should detect the incidence and switch immediately to the backup laser without interrupting the accelerator operation. A schematic of such a redundant system is depicted in figure 5. Two identical lasers are connected to switches (fast acousto-optic modulators AOM) and combined in a coupler, amplified and fed to the fiber links. The modulators have a risetime of 10 ns, so the switching process is fast. A challenge is to verify that the lasers are working as specified. A single diagnostic method cannot exclude all possible modes of failure, for example a degradation in phase noise is not necessarily accompanied with a loss of mode-lock. To guarantee operational safety, the optical spectrum, average and peak power of the laser pulses and the phase noise need to be continuously monitored.

If the operational laser fails and the backup laser has to take over, it is mandatory that the phase of the pulses relative to the RF remains exactly as it was before. The feedback locking the lasers to the 1.3 GHz RF of FLASH uses the 24th harmonic of the laser repetition frequency (54 MHz). Hence there are 24 different phases at which the laser pulse train can be locked to the RF. To avoid ambiguities, a second feedback loop operating at half the laser repetition rate is foreseen. This feedback will catch first and only then the 1.3 GHz feedback will take over. Thus it is ensured that after a restart or swap of the lasers, the phase of the pulse train relative to the RF reference will always be the same.

The system is realized using a Field Programmable Gate Array (FPGA) which is capable of serving as a loop filter for multiple feedbacks and performing the exception handling. The complete system has been set up and first tests with a digital control loop have been carried out and the residual jitter has been found comparable to that of a purely

analog PLL.

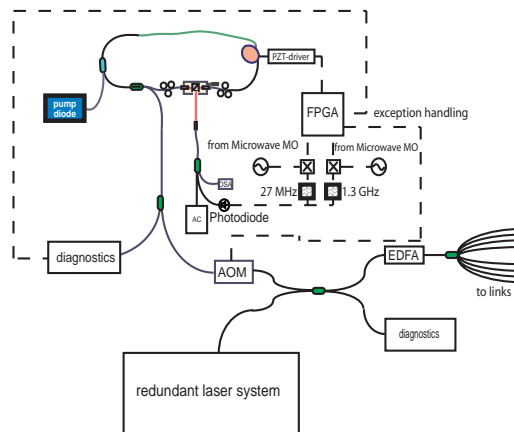


Figure 5: Schematic of the LMO System for the FEL facility FLASH at DESY.

CONCLUSION AND OUTLOOK

We have demonstrated that mode-locked fiber lasers producing a periodic train of sub-ps pulses can serve as ultra-low noise master oscillators for timing and phase reference distribution in next-generation light sources. An LMO system with record-low timing jitter of 10 fs in a bandwidth from 1 kHz up to the 20 MHz has been realized. Successful operation of a complete timing distribution system consisting of the laser master oscillator locked to an S-band reference oscillator and a 500 m-long stabilized fiber link has been demonstrated for the first time. The residual timing jitter caused by the fiber link is 12 fs rms at frequencies between 0.1 Hz and 5 kHz. Furthermore, we have presented a first version of an optical master oscillator system for FLASH which will be implemented and tested starting in early 2007.

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