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.

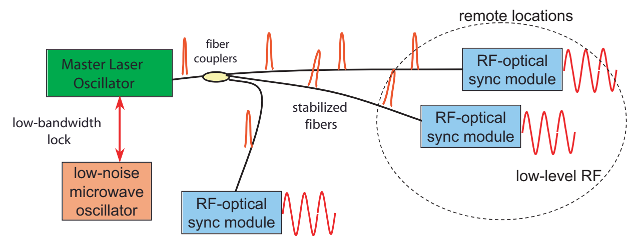

Figure 1: Schematic of the optical timing synchronization system.

INTRODUCTION

One of the key challenges for X-ray free electron lasers is to implement a radio-frequency (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 60 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 ultra-stable 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 photo diode 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 a natural choice 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 component base available at the optical communications wavelength of 1550 nm. Recently, their technical capabilities have also improved significantly [3, 4]. Fiber lasers can generate pulses from picosecond down to 35 fs in duration by simultaneous phase coherent lasing of multiple longitudinal modes spaced in frequency by the pulse repetition rate of the laser. During photo detection, these optical modes beat in the photo detector and generate all harmonics of the repetition rate within the bandwidth of the photo detector.

Mode-locking is initiated by a mechanism providing lower loss (hence, higher net gain) for a pulse than for continuous wave (cw) radiation, leading to pulse formation from intra-cavity noise as soon as the laser reaches a certain intra-cavity power. In the case of active mode-locking, this is a high-speed modulator. For passively mode-locked lasers, this is achieved by a real or artificial saturable absorber. For brevity, we restrict the following description to passive mode-locking. Once the pulses are shortened, the laser dynamics are dominated by an interplay of group velocity dispersion (different frequencies have different speeds) and Kerr nonlinearity (the refractive index depends on intensity), leading to the formation of soliton-like pulses, which intrinsically balance dispersion and nonlinearity [5]. As the gain has a finite bandwidth, the generated pulses need to be stabilized by the saturable absorber, which favors the pulse and suppresses any cw-radiation. At the simplest level, short-pulse laser dynamics can be characterized by four processes: gain, saturable absorption, Kerr nonlinearity, and dispersion interacting in a repetitive way, defined by the optical cavity (Fig. 2a).

In fiber lasers, the fiber assumes multiple roles: It provides nonlinear and dispersive effects that dictate the soliton-like pulse shaping mechanism, and moreover it shields against fast environmental fluctuations. The Erbium- or Ytterbium-doped fiber segments form the gain medium, which is pumped conveniently by low-cost, fiber-

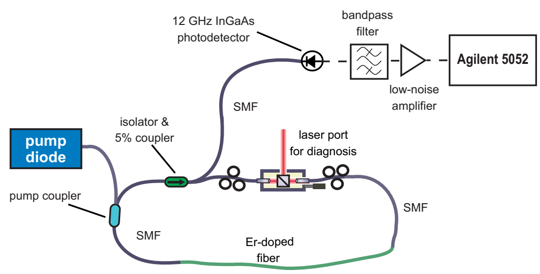

Figure 2: (a) The four effects governing pulse shaping in mode-locked lasers. (b) Schematic of the experimental setup: SMF, single-mode fiber.

coupled 980 nm diode lasers. A representative schematic of the laser is presented in Figure 2b, where saturable absorption is implemented by nonlinear polarization rotation in the fiber.

NOISE PERFORMANCE OF MODE-LOCKED FIBER LASERS

It is essential that the laser serving as the master oscillator has extremely low timing jitter, particularly at high frequencies ($>$ 10 kHz), where further suppression through feedback is difficult. The timing of the pulse circulating in the laser cavity is affected by the intrinsic noise sources such as pump noise and amplified spontaneous emission noise from the amplification process. Ultimately, the timing jitter is limited by quantum fluctuations in the number of photons making up the pulse and the incoherent photons added in the cavity due to spontaneous emission.

The noise characteristics of mode-locked lasers is well-described using soliton-perturbation theory, along with quantum noise sources [6, 7]. These perturbations cause fluctuations in amplitude, phase, timing and center frequency. The last of these further contributes to timing in the presence of dispersion, *i.e.* a shift in center frequency is translated into timing shift *via* dispersion, which is known as the Gordon-Haus effect [8]. For a fundamentally mode-locked fiber laser with small net dispersion and otherwise typical parameters, the quantum-limit is extremely small, on the order of 1 fs (from 1 kHz to 25 MHz, for a repetition rate of 50 MHz).

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 fulfill these requirements (see Figure 3). 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 [10]. It produces 1 nJ pulses of $\geq$ 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 3 shows the single sideband phase noise spectrum of the harmonic at 1.3 GHz, extracted from the pulse train after photo detection and filtering. This phase noise spectrum can be converted into a timing jitter using

$$\Delta t = \frac{\sqrt{2\int L(f')df'}}{2\pi f_0}. \quad (1)$$

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.

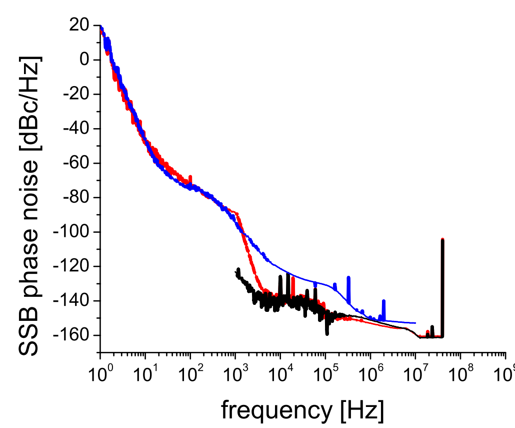

Figure 3: Spectral density of single-sideband phase noise for the free-running EDFL (black), the RF reference oscillator used to lock the EDFL (blue), and the EDFL locked to the reference (red).

The amplitude noise of the fiber lasers has also been characterized. Figure 4 shows the relative intensity noise (RIN) of both lasers from 10 Hz to 1 MHz. The EDFL shows slightly lower high-frequency noise than the YDFL, which may be due to the different amplifier media and pulse shaping processes at work. The integrated RIN measured from 10 Hz to 1 MHz is about 0.04% rms for the

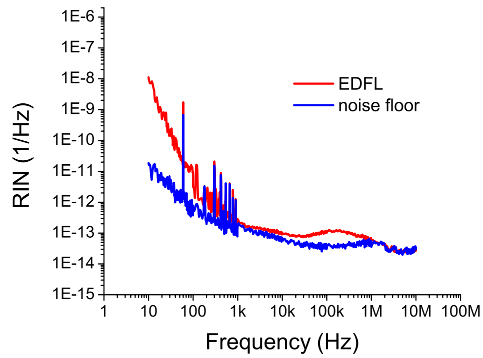

Figure 4: Relative intensity noise (RIN) of the EDFL, along with the measurement noise floor.

YDFL, and 0.03% rms for the EDFL, compared to the average power level. The amplitude noise level of these lasers is important for diagnostic measurements making use of the amplitude of the laser pulses to measure e.g. the beam position or arrival time [12, 13].

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 5. 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 ($\delta t/t \sim 10^{-6}/°C$ [11]). 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 the fiber are detected using two high-bandwidth photo diodes. 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 photo

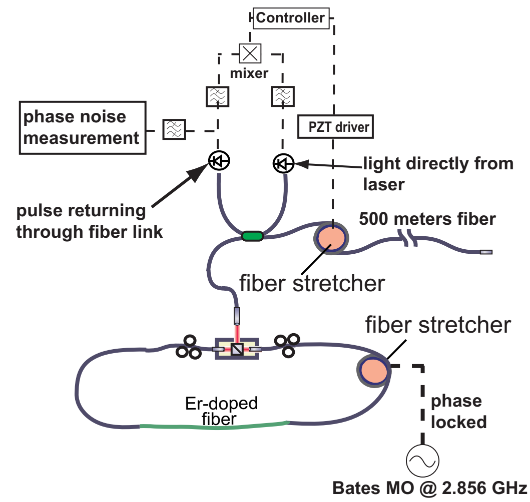

Figure 5: Schematic setup of the setup at the MIT Bates Laboratory.

diodes 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 6. 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.

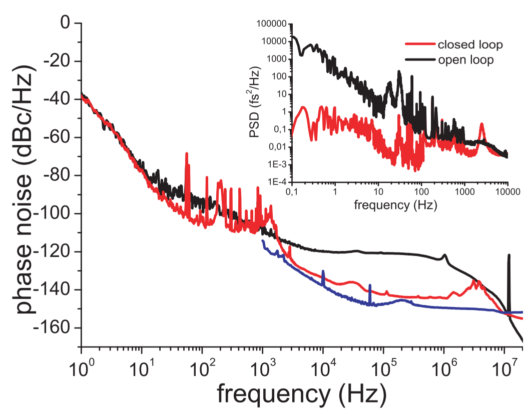

Figure 6: Single sideband phase noise of the Bates Master Oscillator (MO) (black), the EDFL locked to the reference after transmission through the link (red) and the free running EDFL (blue). Inset: Mixer output signal of the RF fiber link stabilization.

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 relevant parameter. Figure 6 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 6, 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 fulfill 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 7. 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 necessarely accompanied with a loss of mode-lock. To guarantee operational safety, the optical spectrum, the 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 24^{th} 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. The residual jitter has been found comparable to that of a purely analog PLL.

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

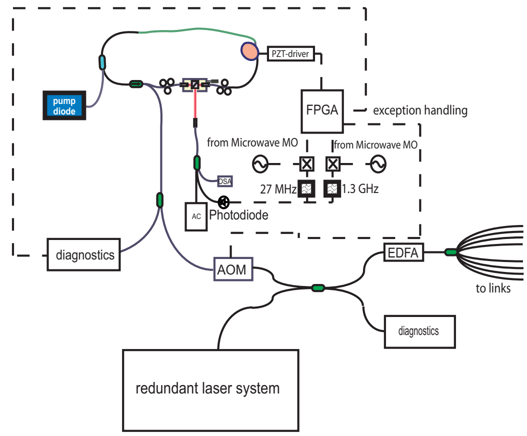

Figure 7: Schematic of the LMO System for the FEL facility FLASH at DESY

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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