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Nuclear Instruments and Methods in Physics Research A 557 (2006) 299–304
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A
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Towards high-performance optical master oscillators for energy recovery linacs

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Available online 18 November 2005

Abstract

Advanced accelerators as well as 4th generation light sources require extremely precise timing distribution. Energy recovery linacs, for example, require precise timing of the electron bunches reentering the linac in order to minimize the disturbance of the RF amplitude and phase to evade resonant effects on the subsequent accelerated bunch. The timing distribution system has to maintain femtosecond precision over lengths ranging from several hundred meters to a few kilometers. We discuss potential optical master oscillators with exceptionally low timing jitter that can be used for ultra-precise timing distribution in such facilities. A promising approach is the use of a mode-locked laser that generates pulses with an ultra-stable repetition rate, distributed through fiber links. A good candidate is a mode-locked Erbium-doped fiber laser, featuring very low high-frequency noise in comparison to presently available microwave sources. Laser systems locked to atomic references are discussed, which may eventually enable synchronization of independent lasers in the facility with potentially few-femtosecond precision as well as pump–probe measurements with attosecond time resolution.

PACS: 42.55.Wd; 42.72.−g; 29.17.+w; 29.20.Lq; 41.60.Cr

Keywords: Accelerators; Optical timing systems; Energy recovery linac; Fiber laser; Frequency standard

1. Introduction

In an energy recovery linac (ERL), electrons are generated in a high brightness electron source, accelerated through a linear accelerator, transported by a magnetic arc lattice to a photon generating device (which can be either an undulator or a free electron laser (FEL)), transported back to the entrance of the linac 180° out of phase for deceleration and energy recovery, and then dumped at an energy close to their injection energy [1]. The energy of a decelerated bunch is used to accelerate the following bunch, recovering virtually all the energy. Therefore, ERLs can accelerate very high average currents with modest amounts of radio-frequency (RF) power, rendering them attractive for a variety of applications.

ERLs impose very stringent requirements on the timing and synchronization system. These requirements are driven by intrinsic constraints of the machine (e.g., beam propagation and stability or machine protection issues) or by external considerations, namely user-specified requirements on spatial and temporal stability of the FEL pulse.

Amplitude and phase stability of the accelerating or decelerating RF inside the cavities of the linac to the order of 10^{-4} and 0.02°, respectively, is mandatory in order to be able to regenerate the beam energy to a 10^{-4} level [2] and thus keep the klystron power needed to sustain a high average beam current to a minimum. This requires point-to-point stabilization of various RF frequencies for the critical components (injector, linac, bunch compressors and experimental area) with femtosecond precision.

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doi:10.1016/j.nima.2005.10.089

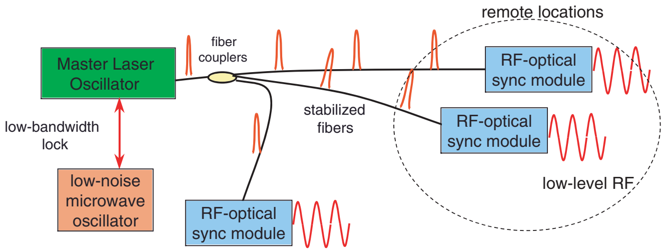

Fig. 1. Schematic of the optical timing synchronization system.

These challenging requirements on the timing stability appear to be beyond the capability of traditional RF distribution systems based on temperature-stabilized coaxial cables. A promising way to reach this goal is by using an optical transmission system, depicted schematically in Fig. 1. A train of sub-picosecond pulses of light generated from a mode-locked laser with very low timing jitter is distributed over actively length-stabilized optical fiber links [3] to an arbitrary number of remote locations. The repetition rate of the pulse train, as well as its harmonics, carry the synchronization information. At the remote locations, low-level RF signals can be extracted simply by using a photodiode and a suitable bandpass filter to pick off the desired harmonic of the laser repetition rate, or by phase-locking an RF source to one harmonic of the pulse train [4].

In this paper, we demonstrate very stable short pulse fiber laser sources with exceptionally low high-frequency timing jitter, which can be used for precise timing distribution down to the sub-50 fs level (Sections 2 and 3). The low-frequency noise will later be suppressed by locking to the microwave master oscillator of the facility. In Section 4, we introduce the concept of an all-optical master oscillator, that would replace the microwave clock of the facility by expanding the optical master oscillator to a full optical clock. This technology recently revolutionized optical frequency metrology [5]. We describe as an example an optical clock based on Ti:sapphire technology and a methane-stabilized HeNe laser [6–8].

Further improvements in optical clock technology may enable attosecond resolution experiments, based on the recently proposed ultra-fast X-ray sources providing attosecond pulses [9] by spectral slicing, and high-precision optical clocks providing timing information with attosecond resolution for pump and probe pulses in a potential experiment.

2. Mode-locked fiber lasers

Mode-locked 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 photodetection, these optical modes beat in the photodetector and generate harmonics of the repetition rate up to the bandwidth of the photodetector.

Mode-locking is initiated by a mechanism providing lower loss (hence, higher net gain) for a pulse than for cw radiation, leading to pulse formation from intra-cavity noise as soon as the laser is turned on. In the case of active mode-locking, this can be a high-speed modulator. For passively mode-locked lasers, this is achieved by a real or artificial saturable absorber. 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 [10]. 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 generation can be understood by four processes: gain filtering, saturable absorber, Kerr nonlinearity, and dispersion interacting in a periodic structure defined by the physical cavity (Fig. 2(a)).

Fiber lasers are a natural choice to realize an optical master oscillator, because of their long-term stability, ease of coupling to the fiber distribution system and the well-developed and mature component base available at the optical communications wavelength of 1550 nm. Recently, there has been a lot of activity in the development of fiber lasers, see for example, Refs. [11,12]. Yb-doped and Er-doped fiber lasers offer stable and practical platforms for short pulse generation at 1 μm [13] and 1.5 μm [14], respectively. Here, the fiber assumes multiple roles, providing nonlinear and dispersive effects that dictate the soliton-like pulse shaping mechanism and moreover shielding against fast environmental fluctuations. The Er- or Yb-doped fiber segments form the gain medium, pumped conveniently by low-cost, fiber-coupled 980 nm diode lasers. A representative schematic of the laser is presented in Fig. 2(b), where saturable absorption is implemented by nonlinear polarization rotation in the fiber [14].

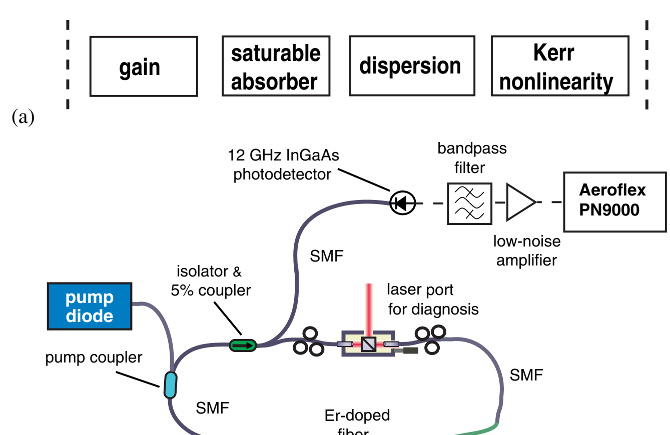

Fig. 2. (a) The four main effects governing pulse shaping in mode-locked lasers. (b) Schematic of the experimental setup: SMF, single-mode fiber.

3. Noise characteristics of fiber lasers

In order to serve as an optical master oscillator, the total timing jitter needs to be on the order of 50 fs in an bandwidth from 1 Hz to the Nyquist frequency of the lasers (~20 MHz) in order to satisfy the amplitude and phase stability requirements of the RF inside the linac cavities. The noise behavior of mode-locked lasers is successfully described using soliton-perturbation theory, along with quantum noise sources [15,16].

Passively mode-locked lasers feature very low high-frequency phase noise levels, but in order to guarantee good low-frequency timing jitter, stabilization to an ultra low-noise RF reference oscillator is required. The high-frequency noise of an erbium-doped (EDFL) and ytterbium-doped fiber laser (YDFL) has been measured using the setup depicted in Fig. 2 [17]. The results are shown in Fig. 3, in comparison with the phase noise of a high-quality RF source (Marconi 2021). At offset frequencies greater than 20 kHz, the EDFL is superior in terms of phase noise level. The high-frequency jitter amounts to 10 fs rms for the EDFL for a bandwidth of 1 kHz to 20 MHz, which is the Nyquist frequency for this laser. We believe that this is mainly due to two effects: (i) The net dispersion of the laser cavity is positive ($\sim +6000\,\mathrm{fs}^2$), so fluctuations in the center frequency of the pulse are directly converted into timing jitter by the non-zero net dispersion of the cavity. This is known as Gordon–Haus jitter [18]. This jitter can be overcome by setting the net dispersion to zero. (ii) In addition, conversion of amplitude to phase (AM-to-PM conversion) noise during the photodetection process plays a significant role. The setup shown in Fig. 4 was used to measure the influence of amplitude fluctuations on the phase noise spectrum of a harmonic of the laser repetition rate. Here, the pulse coming from the laser oscillator is split and directed onto two separate photodetectors, where the power incident on one diode is adjustable using a variable neutral density filter. A harmonic of the laser repetition rate is picked from both photodetectors using an appropriate bandpass filter, amplified and mixed. The phase offset between the two RF signals is set to zero using a phase shifter. The resulting phase change as a function of incident power is shown in the inset to Fig. 4. The AM-to-PM conversion coefficient varies between 1 ps/mW and 10 ps/mW, depending on the type of photodiode and biasing voltage. Given the measured amplitude noise of the EDFL, we deduce an added timing jitter of as much as ~5 fs in a bandwidth from 10 kHz to 20 MHz, which is a significant fraction of the total noise. The influence of AM-to-PM conversion can in principle be reduced by stabilizing the incident power by employing a feedback from the detected signal to an amplitude modulator placed before the photodetector, which will be pursued in the future.

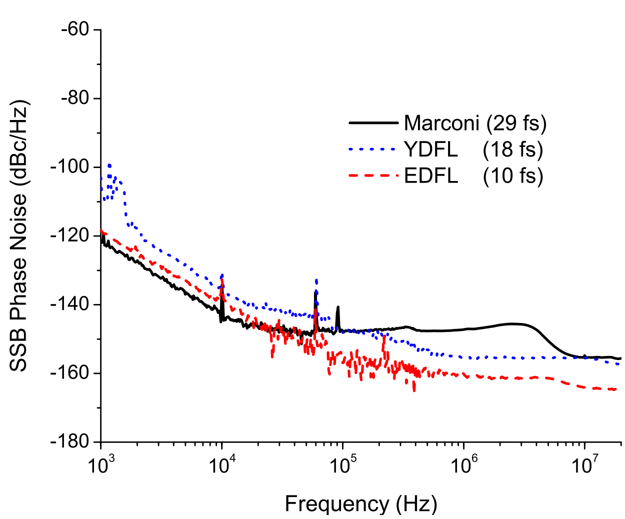

Fig. 3. Single-sideband phase noise of the YDFL (dotted line), EDFL (dashed line) and Marconi 2021 (solid line). The measurements are scaled to a carrier frequency of 1 GHz.

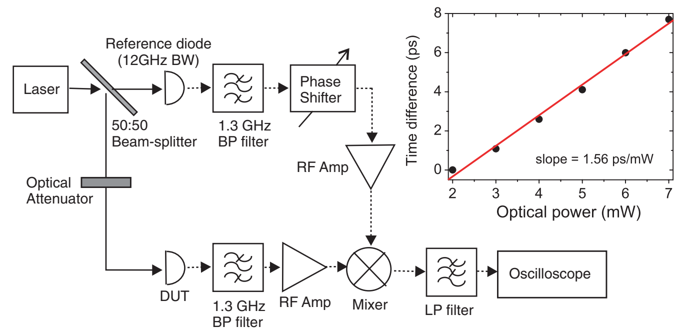

Fig. 4. Experimental setup for AM-to-PM conversion measurements of photodetectors.

4. All-optical master oscillator

In the future, it may be necessary to improve the close-in noise of the optical master oscillator to beyond the level of performance that can be achieved by simply locking the master laser to a conventional RF source. To impose this low close-in noise behavior onto the repetition rate of the optical master oscillator, we can utilize the optical frequency comb of the mode-locked laser and construct an optical clock [19]. Here, the key is to phase-coherently reference the optical frequency comb to an optical atomic reference line. It is expected that these optical clocks will even outperform cesium clocks on which current time keeping is based [19]. Such systems could provide independent high-precision timing signals at different locations of the system. After the measurement only an absolute timing shift between the two reference systems has to be recorded. The two systems only need to be synchronized on a time scale where appreciable drift between the two pulse trains has occurred. It is conceivable that in this way attosecond resolution measurements can be performed while the absolute synchronization between two locations is only maintained to a few femtosecond precision.

The optical spectrum of a mode-locked laser consists of thousands of longitudinal modes, separated by the

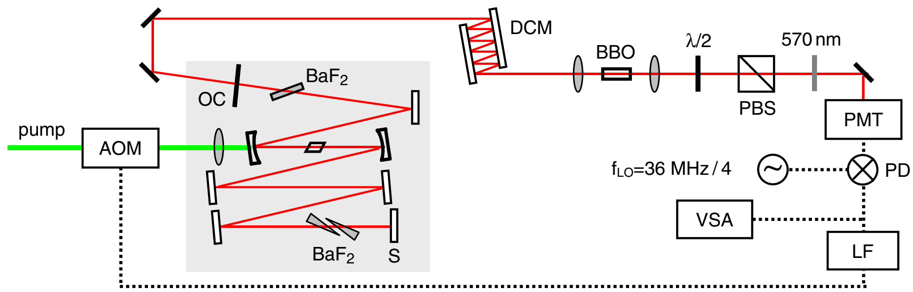

Fig. 5. Carrier-envelope phase stabilized 200 MHz octave-spanning Ti:sapphire laser. The femtosecond laser itself is indicated by the grey area. AOM, acousto-optical modulator; S, silver end mirror; OC, output coupling mirror; PBS, polarizing beam splitter cube; PMT, photomultiplier tube; PD, digital phase detector; LF, loop filter; VSA, vector signal analyzer. The carrier-envelope frequency is phase locked to 36 MHz [25].

repetition frequency of the cavity, forming a frequency comb. These comb lines are given by $f_{\mathrm{comb}} = f_{\mathrm{ce}} + mf_{\mathrm{rep}}$, where f_{rep} and f_{ce} denote the repetition frequency and carrier-envelope frequency, respectively; m is an integer. In order to relate the repetition rate to an optical reference line, both degrees of freedom (f_{rep} and f_{ce}) need to be controlled. As the integer m is on the order of 10^6, even a loose phase stabilization ($\sim 10^\circ$) of the carrier-envelope phase and one selected comb line frequency (when using optical frequencies as sources for the beat signal) is sufficient to achieve very small residual timing jitters. This can be understood by taking into account that the reference frequency for stabilization is in the 100 THz range. Thus, time per degree of phase is orders of magnitude smaller than for microwave frequencies commonly used to synchronize the repetition rate of mode-locked lasers [20].

In the time domain, the carrier-envelope phase is a measure of the relative position of the optical carrier wave within the pulse envelope. In the frequency domain, the change in carrier-envelope phase leads to an offset of the comb lines from zero, $f_{\mathrm{ce}} = (\Delta\phi/2\pi)f_{\mathrm{rep}}$. If this offset is not stabilized, the absolute position of the comb lines is changing over time even though the repetition rate is constant.

4.1. Stabilization of the carrier-envelope phase

The carrier-envelope phase is commonly stabilized by using f-to-$2f$ self-referencing [19]. This implies taking the low-frequency part of the spectrum, frequency doubling it and beating this newly generated light with the high-frequency part of the original spectrum emitted by the laser. Thus, an octave-spanning spectrum is needed. This can be achieved by either using external spectral broadening of the output of a fiber or solid-state laser in a microstructure fiber [21,22] or a special Ti:sapphire laser built to generate an octave-spanning spectrum [23,25]. A typical experimental setup to generate the stabilization signal is shown in Fig. 5. The Ti:sapphire output is focused into a 2 mm thick BBO crystal to generate the second harmonic of the low-frequency part of the spectrum. After spectral filtering, the interference beat is detected using a photomultiplier tube. The measured RF power spectrum shows a carrier-envelope beat signal with a signal-to-noise ratio of 35 dB within a 100 kHz resolution bandwidth, sufficient for direct carrier-envelope phase stabilization. The error signal is created by mixing the beat signal with a reference source. The loop is closed by feeding the error signal to an acousto-optic modulator placed in the pump beam (see Fig. 5) which modulates the pump power and thus changes the carrier-envelope frequency. Fig. 6 shows the power spectral density (PSD) of the carrier-envelope phase fluctuations. The integrated phase error from 2.5 mHz to 10 MHz is 0.10 rad corresponding to 45 attoseconds of carrier-envelope timing jitter. Thus, the carrier-envelope phase can be stabilized to very high precision.

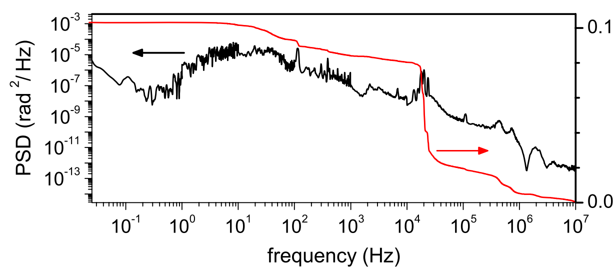

Fig. 6. Residual phase noise of the carrier-envelope phase [25].

4.2. Stabilizing the repetition rate

There are several optical frequency standards available which can be used to stabilize the repetition rate of frequency combs and for the construction of optical clocks [24]. A very compact, transportable and therefore practical solution for such a frequency standard is the double-mode helium neon laser stabilized to the $\mathrm{F}_2^{(2)}$ [P(7), ν_3] optical transition in methane at 3.39 μm [8]. An optical clock using this source has been demonstrated recently [7].

The experimental setup used in this experiment is shown in Fig. 7. The laser source is a Ti:sapphire laser with an output coupler, custom-designed to emit an optical spectrum with peaks around 670 and 834 nm [6]. The difference frequency between these two spectral components generated in a periodically-poled lithium niobate (PPLN) crystal is 3.39 μm, corresponding to the wavelength

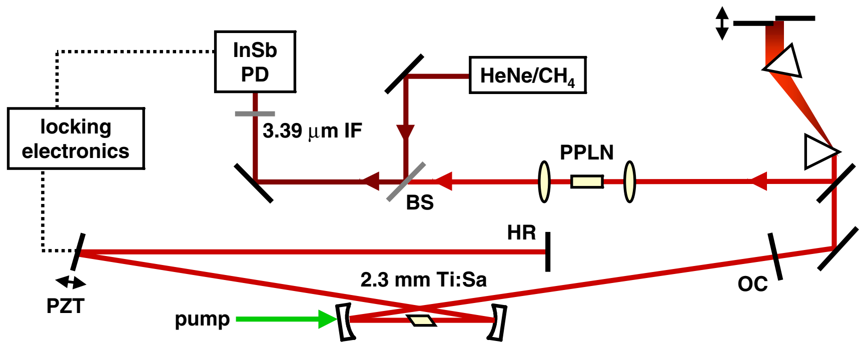

Fig. 7. Schematic of the DFG optical clock scheme [7].

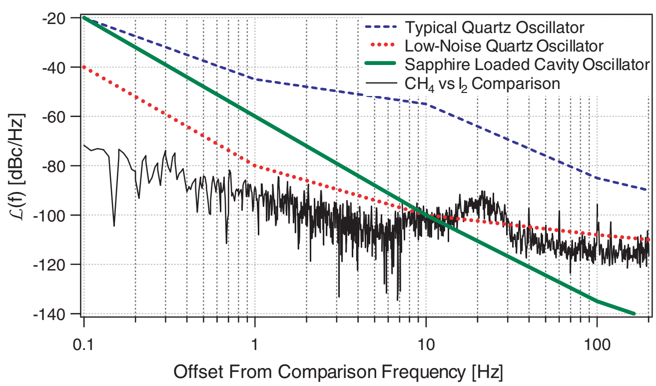

Fig. 8. SSB phase noise of the CH_4 clock signal when compared to an iodine clock signal. Additional curves show the approximate single-sideband phase noise of extremely low-phase-noise microwave sources for comparison. All data were scaled to a 1-GHz carrier [7].

emitted by the stabilized HeNe laser. These two frequencies are combined and the beat between these two is detected by a photodetector. Control of the repetition rate is obtained by feedback of the phase-lock-loop error signal to a piezoelectric transducer on which the folding mirror of the Ti:sapphire cavity is mounted. Fig. 8 indicates a phase noise of -70 dBc/Hz at an offset frequency of 100 mHz [7], which is 25 dB better than the typical value for a low-noise crystal oscillator. The results shown in Fig. 8 have been scaled to 1 GHz to facilitate the comparison of the performance of various sources. In this case, the single-sideband phase noise was limited by the noise of the RF amplifiers used and the AM-to-PM conversion in the photodetector.

5. Conclusion and outlook

Towards a mode-locked laser-based synchronization system for next generation accelerators and light sources has made significant advances. Synchronization at the 10 fs level seems feasible within the next few years. Energy recovery linacs impose significant constraints to the synchronization system to guarantee optimal machine performance and low timing jitter of the X-ray pulses. A mode-locked fiber laser based timing system seems a very promising approach to meet the specifications of future ERLs. It can be argued that large scale femtosecond timing distribution together with the development of high-precision optical clocks will enable attosecond resolution X-ray pump–probe experiments in the not too distant future.

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