PHASE NOISE CHARACTERISTICS OF FIBER LASERS AS POTENTIAL ULTRA-STABLE MASTER OSCILLATORS

Axel Winter, Peter Schmüser, Universität Hamburg, Hamburg, Germany,
Holger Schlarb, DESY, Hamburg, Germany,
F. Ömer Ilday, Jung-Won Kim, Jeff Chen, Franz X. Kärtner,
Massachusetts Institute of Technology, Cambridge, MA, USA.

Abstract

Fourth-generation light sources, such as the European X-Ray Free Electron Laser facility (XFEL), require timing signals distributed over distances of several kilometers with a timing jitter in the order of femtoseconds. The master clock for the proposed optical distribution system must operate with exceptionally low timing jitter. A promising approach is the use of a mode-locked laser that generates ultrastable pulses which are distributed via timing stabilized fiber links. Mode-locked Erbium-doped fiber lasers are attractive candidates, featuring very low noise at high frequencies. In this paper, we present a study of the phase noise of various mode-locked fiber lasers in view of their applicability as laser-based master oscillators for femtosecond-level timing distribution.

INTRODUCTION

One of the key challenges for the new fourth generation light sources such as the XFEL is to implement a timing stabilization and distribution system that allows the full exploitation of the potentially 10 fs x-ray pulse for time resolved studies. To this end, the electron beam needs to enter the undulator with timing jitter comparable to the pulse duration, which puts significant pressure on the synchronization system of the XFEL and requires a point to point stabilization of various RF frequencies for the critical components (booster section, injector, bunch compressors and experimental area) with femtosecond precision.

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 Figure 1. A train of sub-picosecond pulses of light generated from a mode-locked laser with very low timing jitter are distributed over actively length-stabilized optical fiber links to an arbitrary number of remote locations. The precise repetition rate of the pulse train, as well as its harmonics, contain 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 the desired harmonic of the laser repetition rate, or by phase locking an RF source to one harmonic of the pulse train [1].

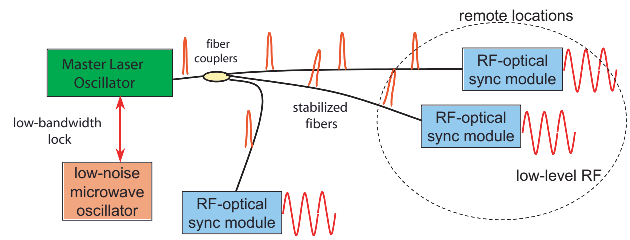

Figure 1: Schematic of the optical timing synchronization system.

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. 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 [2]. 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 absorber, Kerr nonlinearity, and dispersion interacting in a periodic structure, defined by the physical cavity (Figure 2(a)).

Fiber lasers are a natural choice to realize an optical master oscillator, because of the ease of coupling to the fiber distribution system, their good long-term stability, and the well-developed and mature component base available at

0-7803-8859-3/05/$20.00

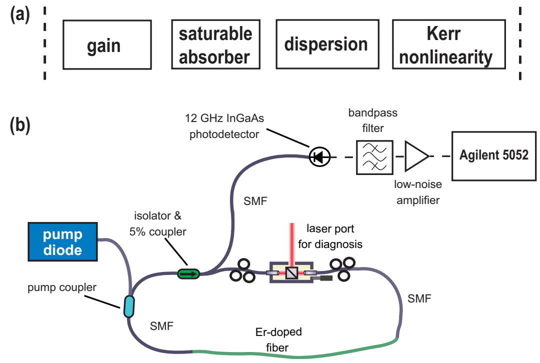

Figure 2: (a) The four effects governing spulse shaping in mode-locked lasers. (b) Schematic of the experimental setup: SMF, single-mode fiber.

the optical communications wavelength of 1550 nm. Recently, their technical capabilities have also improved significantly [3]. Yb-doped and Er-doped fiber lasers offer stable and practical platforms for short pulse generation, at $1\mu\text{m}$ and $1.5\mu\text{m}$, 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 Figure 2(b), where saturable absorption is implemented by nonlinear polarization rotation in the fiber.

LIMITS TO LASER NOISE

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 noise is limited by quantum noise on the number of photons making up the pulse.

The noise behavior of mode-locked lasers is successfully described using soliton-perturbation theory, along with quantum noise sources [4, 5]. 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. For a fiber laser with small net dispersion and otherwise typical parameters, the quantum-limit is extremely small, in the other of 1 fs (from 1 kHz to 25 MHz, for a repetition rate of 50 MHz).

EXPERIMENTAL SETUP AND RESULTS

The noise performance of both an Er-doped fiber laser (EDFL) and an Yb-doped fiber laser (YDFL) were characterized. The EDFL is a stretched-pulse Er-fiber laser [6] producing pulses compressible down to 100 fs and 1 nJ of energy at a repetition rate of 36 MHz, centered at 1550 nm. A schematic of the EDFL and the experimental setup is shown in Figure 2. The YDFL is configured to produce pulses compressible down to 70 fs with 2 nJ energy content, with a repetition rate of 36 MHz, centered at 1030 nm [3]. The YDFL (not shown) has a cavity similar to that of the EDFL. Both of the lasers are free-running, in the sense that the cavity length is uncontrolled and subject to slow, thermally induced fluctuations.

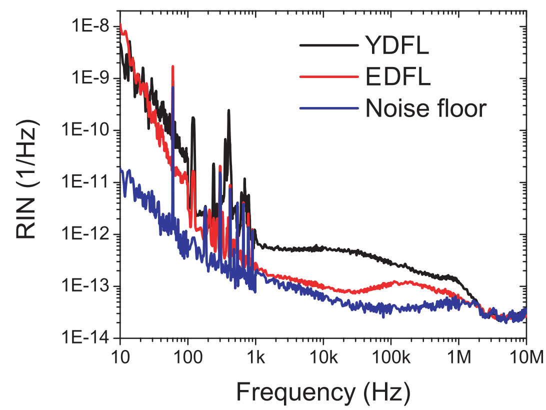

Figure 3: Relative intensity noise (RIN) of the EDFL and YDF, along with the measurement noise floor.

Figure 3 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 might be due to the different amplifier media and pulse shaping processes at work. The integrated RIN measured from 10 kHz to 1 MHz is about 0.04% rms for the YDFL, and 0.03% rms for the EDFL, compared to the average power level. Figure 4 shows the single sideband phase noise spectrum of the harmonic at 1.3 GHz extracted from the pulse train upon photo detection and filtering. This phase noise spectrum can be converted into a timing jitter using $\Delta t = \sqrt{2\int L(f')df'}/2\pi f_0$. The integrated timing jitter from 10 kHz to the Nyquist bandwidth (18 MHz) is about 18 fs and 48 fs for the YDFL and EDFL, respectively. For comparison, the phase noise of a very low noise frequency generator, Marconi 2041, is also plotted. As the lasers are free running, the performance of the microwave oscillator is superior in the low frequency regime ($<$ 10 kHz), but at frequencies of $\sim$ 100 kHz, the mode locked lasers reach a comparable level of stability, with the YDFL having the lowest noise among the three at frequencies higher than 200 kHz. We attribute the higher phase noise of the EDFL to its non-zero intra-cavity dispersion ($\sim$ $+6000\text{fs}^2$), which leads to significant Gordon-Haus jitter.

Both lasers would be already suitable for an overall sub-

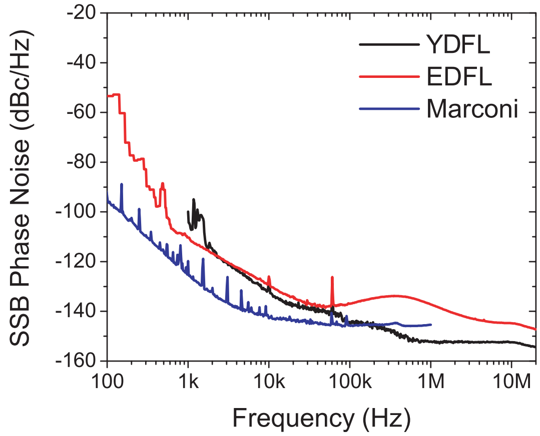

Figure 4: Single-sideband phase noise spectral density for the EDFL, YDFL, and a Marconi 2041 signal generator.

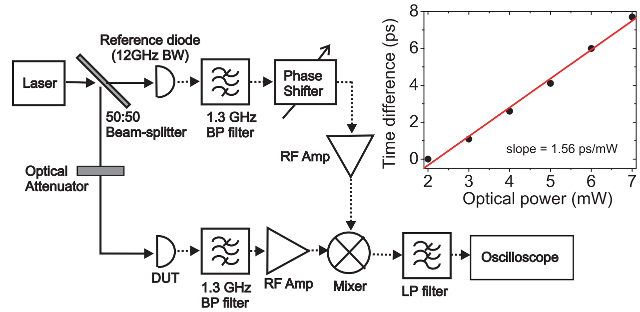

Figure 5: Experimental setup for the measurement of the AM-to-PM conversion during photodetection. Inset: Measured temporal off-set as a function of optical power at a reverse bias voltage of 6 V.

100 fs timing distribution system, which is an important next step to achieve in several FEL facilities. On the long run, the EDFL seems to be a stronger candidate for a master oscillator due to the availability of a large variety of components at 1550 nm, as well as transmission fibers with both signs of dispersion, allowing net zero dispersion fiber links to be constructed. The next version of the EDFL will also operate at zero dispersion, reducing its phase noise to the level of the YDFL.

The timing jitter for both lasers is substantially higher than the noise limit given by the spontaneous emission noise. An important contribution to the measured timing jitter results from conversion of the optical pulse train into microwave signal in the photodetector. Photodetection is limited in prescision by amplitude-to-phase conversion (AM-to-PM) [7]. In other words, the intrinsic noise of the lasers may be substantially lower than what has been measured. Hence, we measured the AM-to-PM conversion for the InGaAs (12 GHz) photodetector used in the measurements. The conversion factor was found to depend on the bias voltage and diode type. For the same InGaAs photodetector (at 6 V reverse bias), the conversion factor is 1.56 ps/mW at 1550 nm. For the EDFL, at a power level of 10 mW on the photodetector, the estimated contribution to phase noise from the photodetection process is *at least 4.2 fs* in the 10 kHz-20 MHz range. A similar value is expected for the YDFL, where 4 fs is already a large fraction of the total timing jitter of 18 fs in this frequency range. A more systematic study is underway to completely characterize and circumvent the limitations imposed by direct detection on timing jitter measurements.

CONCLUSION AND OUTLOOK

In conclusion, mode-locked lasers producing sub-ps pulses are emerging as ultra-low noise master oscillators for timing distribution in next-generation light sources. The main advantage of mode-locked fiber lasers is the excellent performance at high frequencies, the high quality and availability of pump sources and components in the 1550 nm wavelength range. Initial measurements show a high-frequency performance comparable to that of microwave oscillators with ultra-low phase noise. We have verified that stretched pulse mode-locked fiber lasers are the natural choice due to the absence of Gordon-Haus jitter for low timing jitter operation and demonstrated a source with record-low timing-jitter of only 18 fs in the high frequency range. Such sources can be made readily available for sub-100 fs and potentially sub-50 fs timing distribution. The true noise of the lasers may indeed be lower, since AM-to-PM conversion in the photodetection process may be limiting the current measurements. The lasers are free running, resulting in high noise at low frequencies (sub-100 kHz), which will be suppressed by locking to the overall master clock of a given facility by a low-bandwidth PLL.

REFERENCES

[1] J. Kim, F. X. Kärtner, and M. H. Perrott, "Femtosecond synchronization of radio frequency signals with optical pulse trains," Opt. Lett. **29**, 2076-2078 (2004).

[2] H. A. Haus, "Mode-locking of lasers," IEEE J. Sel. Top. Quantum Electron. **6**, 1173-1185 (2000).

[3] F. Ö. Ilday, J. R. Buckley, H. Lim, and F. W. Wise, "Generation of 50-fs, 5-nJ pulses at 1.03 μm from a wave-breaking-free fiber laser," Opt. Lett. **28**, 1365-1367 (2003).

[4] S. Namiki, and H. A. Haus, "Noise of the stretched pulse fiber ring laser: Part I - Theory," IEEE J. Quantum Electron. **33**, 649-659 (1997).

[5] C. X. Yu, S. Namiki, and H. A. Haus, "Noise of the stretched pulse fiber ring laser: Part II - Experiments," IEEE J. Quantum Electron. **33**, 660-668 (1997).

[6] K. Tamura, E. P. Ippen, H. A. Haus, and L. E. Nelson, "77-fs pulse generation from a stretched-pulse mode-locked all-fiber ring laser," Opt. Lett. **18**, 1080-1082 (1993).

[7] E. N. Ivanov, S. A. Diddams and L. Hollberg, "Analysis of noise mechanisms limiting the frequency stability of microwave signals generated with a femtosecond laser", IEEE J. Sel. Top. Quantum Electron. **9**, 1059-1065 (2003).

