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ALL-FIBER PHOTONIC, ULTRALOW-NOISE, ROBUST OPTICAL AND MICROWAVE SIGNAL GENERATORS FOR FELs AND UED

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Abstract

Optical timing and synchronization is becoming a more important and essential element for future ultrafast X-ray and electron science [1, 2]. As a result, compact, ultralow-noise, mechanically robust and long-term stable optical/microwave signal generators are highly desirable for future XFELs and UEDs. Here we show that the combination of mode-locked fiber laser and fiber delay-based stabilization method enables the generation of ultralow-noise optical and microwave signals. We show that all-PM fiber lasers can provide excellent mechanical robustness: stable laser operation over >1 hour is maintained even in continuous 1.5g vibrations [3]. Using a compactly packaged fiber delay as the timing reference, we could stabilize the repetition-rate phase noise of mode-locked lasers [4, 5] down to -100 dBc/Hz and -160 dBc/Hz at 1-Hz and 10-kHz offset frequency, respectively, at 1-GHz carrier, which corresponds to only 1.4 fs rms absolute timing jitter [1 Hz - 100 kHz]. With DDS-based electronics, low-noise and agile microwave frequency synthesizer was also realized [6]. This new class of photonic signal generator will be suitable for master oscillators in various accelerator-based light sources.

INTRODUCTION

Robust operation of mode-locked lasers is highly desirable for optical timing and synchronization of free electron lasers (FELs) and ultrafast electron diffraction (UED). In accelerator facilities, the environment is often harsher than well controlled optics laboratories due to vibrations, radiation and high voltage and current pulsed signals. Although nonlinear polarization evolution-based mode-locked lasers have been widely used to generate low-noise timing signals, the mode-locking state is sensitive to environment-induced perturbations. In order to operate the mode-locked lasers in a long-term stable way in these facilities, mechanical robustness is important. As a solution, polarization-maintaining fiber-based mode-locked lasers have been investigated because strong birefringence relieves the environment sensitivity.

In addition, for effective optical timing and synchronization, low timing jitter is very important. Mode-locked lasers have shown great short-term timing jitter. Typically, timing jitter (i.e., repetition-rate phase noise) of free-running laser oscillator is fs-level within ~ms time scale. However, it starts diverging over time due to lack of restoring force. Therefore, locking laser oscillator to more longer-term stable reference is highly desirable to maintain great short-term timing jitter over longer time scale. Many microwave reference oscillators and optical references have been used to lock the mode-locked lasers. Among them, an ultra-stable Fabry-Perot cavity-based locking system has been an effective way to suppress timing jitter over ~10 s time scale. However, it is a high-cost instrument and technically difficult to implement outside of well-controlled laboratories. As an alternative way of timing stabilization, fiber delay line-based technique was developed [4].

In this paper, a simple structured polarization-maintaining fiber-based mode-locked laser is discussed. We examined the mechanical robustness of an all-PM 3 x 3 coupler-based nonlinear amplifying loop mirror (NALM) mode-locked laser under > 1 hour of $1.5g_{rms}$ vibration condition. Also, a continuous operation of graphene saturable absorber (SA) based mode-locked laser under gamma ray radiation is also discussed [7]. To reduce short-term timing jitter, a compact, robust and all-fiber delay line-based timing jitter suppression technique is introduced. By combining the robust laser with the fiber-based timing jitter stabilization technique and DDS-based electronics, ultralow-noise optical/microwave synthesizer, which can be effectively used for FELs and UED facilities, is demonstrated.

RESULTS

We demonstrated a simple structured, mechanically robust 3 x 3 coupler-based all-PM fiber laser [Schematic shown in Fig. 1(a)]. A 3 x 3 coupler has intrinsic 120 deg phase bias between each port so that it does not require any additional phase shifter to initiate mode-locking in NALM laser. Moreover, mode-locking threshold is reduced compared to 2 x 2 coupler-based PM-NALM laser.

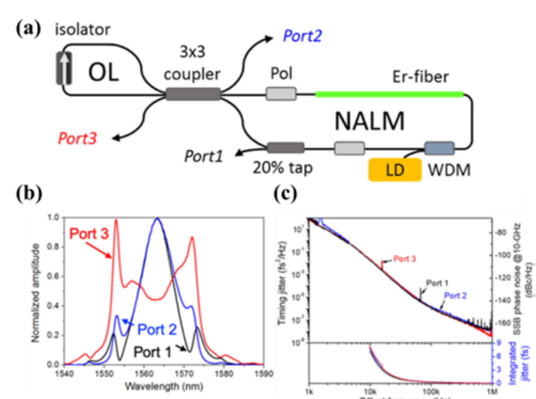

Figure 1: (a) Schematic of an all-PM-fiberized 3 x 3 coupler based NALM laser (b) optical spectra and (c) timing jitter spectra from each port. The data and figures are based on [3].

We can use three fiberized outputs from the 3 x 3 coupler -based PM-NALM laser. Figure 1(b) shows normalized optical spectra of each port, which respectively has

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21.6 nm, 15.1 nm, and 14.1 nm bandwidth at 1560-nm center wavelength. Figure 1(c) shows timing jitter power spectral density spectra. The integrated rms jitter from each port is sub-10-fs [10 kHz – 1 MHz]. The mechanical stability of the laser is tested under >1 hour of 1.5g_{rms} vibration on the shaker table (B&K, LDS 721) [Fig. 2(a)]. Note that this level of vibration is above the level in air-crafts, trucks, and boats, which underlines the mechanical robustness of the demonstrated NALM laser. The optical spectra measurement under 1 hour is shown in Figure 2(b). The mode-locked state is maintained robustly even with strong and continuous mechanical perturbation.

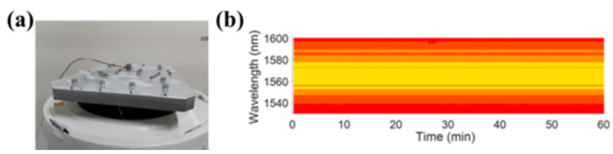

Figure 2: Vibration test of all-PM-fiberized 3 x 3 coupler based NALM laser. (a) The shaker generates 1.5g_{rms} vibration and (b) optical spectrum from the port 1 is recorded for >1 hour. Note that the data and figure are based on [3].

Robust laser operation under radiative environment can be also attractive for the use in accelerator facilities. We examined the use of a graphene saturable absorber in mode-locked fiber lasers [schematic shown in Fig. 3(a)] as a way to achieve robust mode-locking operation in radiative environment. An average irradiation dose rate of 45 Gy/hr and total dose of 2 kGy radiation was applied to the graphene saturable absorber. From the RF pulse train and optical spectrum measurement result under radiation up to 2 kGy in Figure 3(b) and Figure 3(c) respectively, we found that it still maintained the mode-locking operation [7], which is more robust compared to the traditional SESAM-based results.

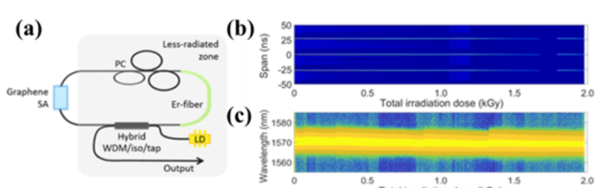

Figure 3: (a) Schematic of a graphene-SA-based mode-locked laser. (b) RF pulse train, and (c) optical spectrum measurement under radiation up to 2 kGy. More detailed information can be found in [7].

Timing jitter of mode-locked lasers diverges over time since there is no restoring force in the laser oscillators. It is highly desirable to stabilize the timing of mode-locked lasers over longer time scales. As a compact and robust timing jitter suppression method, we demonstrate a fiber delay line-based timing jitter suppression technique [4]. The basic principle is to use optical fiber delay as the timing reference and to detect frequency noise of two optical frequency, $f_m = m f_{rep} + f_{ceo}$ and $f_n = n f_{rep} + f_{ceo}$. Then, common mode f_{ceo} noise is rejected by frequency mixer, resulting in $(m-n) f_{rep}$ (~2.5 THz when f_m=194.8 THz and f_n=192.3 THz) noise detection. Therefore, sensitivity (2.5 THz) of noise detection is much enhanced compared to microwave-based technique (GHz-level). The schematic and photo of compact setup are respectively shown in Figure 4(a) and Figure 4(b). The entire system size is ~ 30 cm x 30 cm x 15 cm, and we are currently improving the size and performance even further. Figure 4(c) and Figure 4(d) show the suppressed timing jitter power spectral densities with 1-km fiber and 10-km fiber, respectively. As a result, the timing jitter is suppressed down to 20 fs (when 1-km fiber is used is used [4]) and 1.4 fs (when 10-km fiber is used [5]). If it is converted to the equivalent single-sideband phase noise at 1-GHz carrier, it corresponds to -100 dBc/Hz and -160 dBc/Hz at 1-Hz and 10-kHz offset frequency, respectively [5].

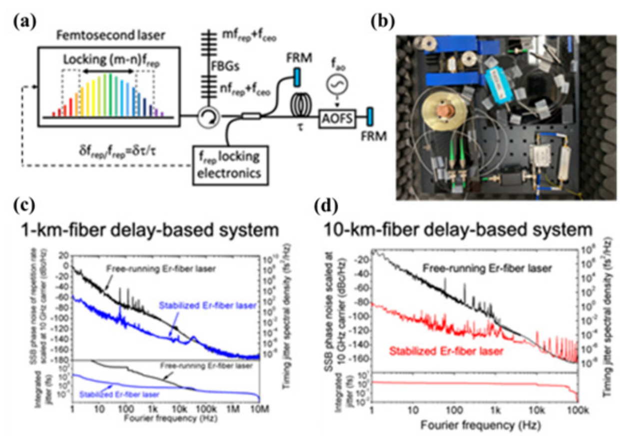

Figure 4: (a) Schematic of fiber delay line-based timing jitter suppression system and (b) setup photo. The suppressed timing jitter power spectral densities when (c) 1-km fiber is used and (d) 10-km fiber is used. Note that the equivalent phase noise is converted for 10-GHz carrier frequency in these plots. More detailed information can be found in refs. [4] and [5].

By adding a fiber-loop optical-microwave phase detector (FLOM-PD, [8]) and DDS electronics, low-noise microwave synthesizer is also demonstrated. Figure 5(a) shows a diagram of it. The repetition rate of mode-locked laser is stabilized by FIRST (Fiber Interferometer based Repetition-rate Stabilization Technique). Then The FLOM-PD (Fiber-Loop Optical-Microwave Phase Detector) is used to generate low-noise microwave using fly-wheel effect between stabilized optical pulse trains with low-timing jitter and a microwave dielectric resonator oscillator (DRO). With commercial DDS electronics, an agile and low-noise 9-11 GHz all-fiber photonic microwave synthesizer is demonstrated [6]. The absolute SSB phase noise and integrated timing jitter of the generated microwave is shown in Figure 5(b). The integrated rms

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riming jitter of the 10-GHz signal is 7.6 fs [10 Hz – 10 MHz], which is limited by PNA noise floor indicated in pink curve. The projected phase noise at 10 GHz measured in optical domain by FIRST setup makes lower integrated jitter, which is 2.6 fs [curve blue].

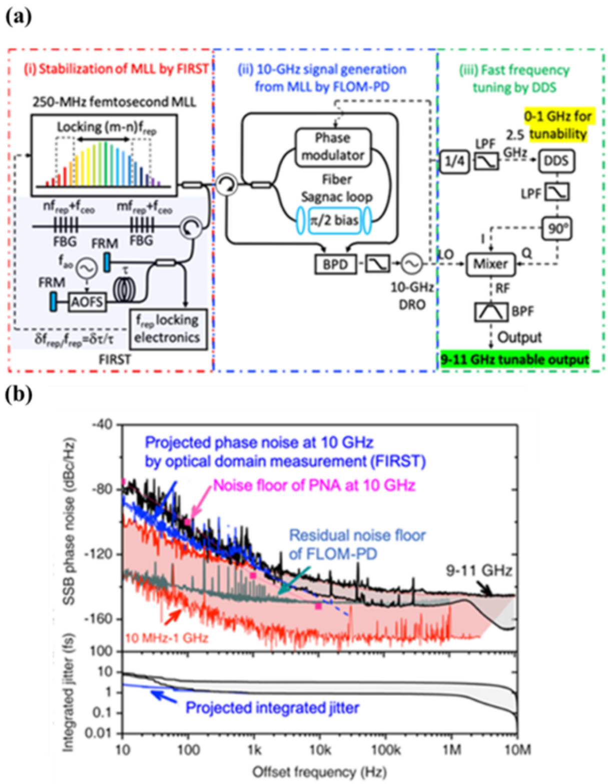

Figure 5: (a) Schematic of the microwave synthesizer. FIRST : Fiber Interferometer based Repetition-rate Stabilization Technique [4,5]. FLOM-PD : Fiber-Loop Optical-Microwave Phase Detector [8]. DDS : Direct Digital Synthesizer. (b) Measured absolute SSB phase noise at 10-GHz and integrated jitter. More detailed information can be found in [6].

CONCLUSION

The all-PM-fiberized 3 x 3 coupler-based NALM laser is demonstrated. The intrinsic 120-degree phase bias decreases system complexity and lowers the mode-locking threshold. Moreover, the all-fiber mode-locked laser shows great mechanical stability, which enables stable operation even under >1 hour of $1.5g_{rms}$ vibration. The graphene saturable absorber-based mode-locked laser can maintain mode-locked operates up to 2 kGy radiation. These features can be advantageous for the operation in FELs and UED facilities.

Further, to improve precise optical timing, a fiber delay line-based timing jitter suppression is applied. The rms timing jitter can be reduced down to 1-fs-level over 1 s time scale. In phase noise, it is -100 dBc/Hz and -160 dBc/Hz at 1-Hz and 10-kHz offset frequency, respectively, for 1-GHz carrier frequency. By combining the DDS electronics with the fiber delay line-locked mode-locked laser, ultralow-noise microwave synthesizer is realized. The demonstrated system synthesizes microwave from 9-11 GHz with low-noise and frequency agility. Note that the center frequency and frequency tuning ranges can be easily changed depending on the intended applications.

Currently we are improving the entire system including better packaging. It is expected robust, compact and all-fiber photonics-based ultralow-noise optical and microwave synthesizers can be readily applied for optical timing and synchronization in FELs and UED facilities in the near future.

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