Attosecond-Jitter Fiber and Waveguide Lasers and Their Ultrahigh-Precision Microwave Photonic Applications

Jungwon Kim[1]

[1]Korea Advanced Institute of Science and Technology (KAIST), Daejeon 305-701, South Korea,
jungwon.kim@kaist.ac.kr

Abstract

I introduce the most recent progress in the development of various types of diode-pumped, attosecond timing jitter fiber mode-locked lasers and their applications in ultrahigh-precision microwave photonic systems.

1. Introduction

Lower timing jitter mode-locked lasers enable sub-cycle pulse synthesis, lower phase noise microwave signal generation, higher speed and higher resolution photonic analog-to-digital converters, more precise local and remote synchronization, and better resolution pump-probe experiments. There has been great progress in the characterization and optimization of timing jitter in ultrafast mode-locked lasers in the recent years. On one hand, the theory of timing jitter in mode-locked lasers has been already well developed from 1990s based on soliton perturbation theory [1], which provided an excellent theoretical framework for the experiments. On the other hand, an accurate characterization of timing jitter in mode-locked lasers over the full Nyquist frequency has been possible by the development of balanced optical cross-correlation (BOC) method [2] in the last few years. As a result, various types of sub-femtosecond timing jitter mode-locked lasers have been demonstrated in 2011-2014 [3-10].

In particular, we have focused on the characterization and optimization of timing jitter in mode-locked fiber lasers, and different types of mode-locked fiber lasers with well below a femtosecond timing jitter have been demonstrated. Compared to the solid-state lasers, fiber lasers have advantages of more compact size, lower cost, less alignment sensitivity and better robustness, which makes them more suitable for applications outside laboratory environments. Moreover, many of design and laser operation principles of fiber lasers can be implemented by waveguide-type lasers as well, which can make such attosecond-jitter mode-locked lasers even more compact and robust. This will enable more widespread use of attosecond-jitter lasers for communication, computation, defense and space applications.

In this paper, I will introduce our most recent progress in the development of attosecond-timing-jitter mode-locked fiber lasers and their applications in ultrahigh-precision microwave photonic systems.

2. Attosecond-jitter mode-locked fiber lasers

It has been predicted that the timing jitter of stretched-pulse fiber lasers mode-locked by nonlinear polarization rotation (NPR) can be in the sub-femtosecond regime [11]. In 2011, by using a sub-20-attosecond-resolution BOC method, we could characterize the timing jitter in mode-locked fiber lasers at different mode-locked regimes (i.e., soliton, stretched-pulse, and self-similar) [12]. We experimentally found that the jitter can be minimized near zero intra-cavity dispersion at stretched-pulse regime, which agrees with the theoretical predictions. This is possible because both the direct timing jitter from the amplified spontaneous emission (ASE) noise and the indirect timing jitter originated from frequency noise and coupled by intra-cavity dispersion (Gordon-Haus jitter) can be minimized in this operation condition. By using this method, the timing jitter of Yb-fiber and Er-fiber lasers could be reduced to 175-attosecond [3] and 70-attosecond [4] jitter, respectively, when integrated from 10 kHz to 40 MHz (Nyquist frequency).

We could further reduce the timing jitter in fiber lasers mode-locked by NPR by shortening the non-gain fiber length. Shorter non-gain fiber enables shorter average pulsewidth and higher pulse energy, which is advantageous for reducing the directly coupled timing jitter. In addition, shorter non-gain fiber reduces excessive higher-order nonlinearity and nonlinear chirp. Therefore, the short non-gain fiber approach can combine the advantages of fiber

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lasers and solid-state lasers for ultralow-jitter photonic sources: it can have better robustness, easier implementation and lower cost of fiber lasers while having similar jitter performance of the best KLM solid-state lasers [10]. The demonstrated timing jitter from a 188-MHz Yb-fiber laser mode-locked by NPR is 15-attosecond when integrated from 10 kHz to 94 MHz offset frequency.

Although the NPR-based fiber lasers could reduce the timing jitter to well below 100-attosecond, long-term stable operation is often limited by birefringence drift in fiber. The availability of all-fiber lasers mode-locked by real saturable absorber devices allows self-starting and long-term stable operation, which make them more suitable for the use outside laboratory environment. We identified that the Gordon-Haus jitter originated from large negative dispersion necessary for soliton mode-locking limits the achievable timing jitter. In order to minimize the Gordon-Haus jitter, we experimentally found the condition where the intra-cavity dispersion magnitude is close to zero while maintaining stable soliton mode-locking. As a result, we could achieve sub-500-attosecond timing jitter when operating a carbon nanotube (CNT)-mode-locked all-fiber Er ring laser at -0.02 ps^2 [8]. Note that a similar approach for lowering jitter can be applied to waveguide lasers mode-locked by real saturable absorber devices as well.

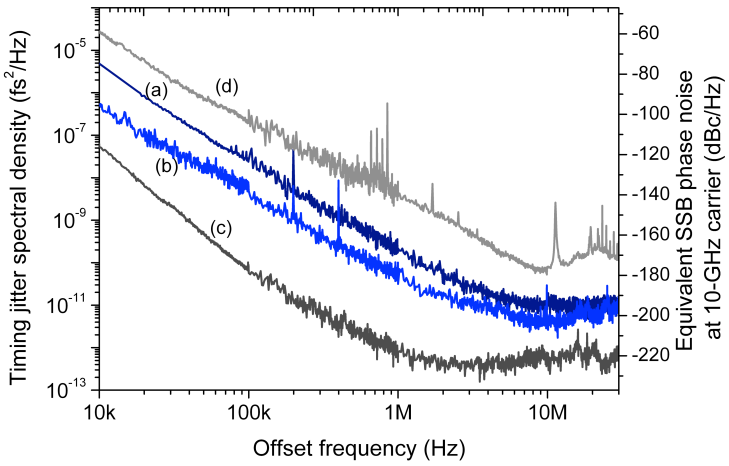

Figure 1. Timing jitter spectral density of various sub-fs-jitter fiber lasers. (a) NPR Yb-fiber laser [3]. (b) NPR Er-fiber laser [4]. (c) NPR Yb-fiber laser with short non-gain fiber [10]. (d) CNT-ML soliton Er-fiber laesr [8].

3. Microwave photonic applications of attosecond-jitter fiber lasers

Using the ultralow jitter mode-locked fiber lasers, we showed some new microwave photonic systems. The first application is ultralow phase noise microwave generation directly from mode-locked fiber lasers. Microwave signals are encoded in the repetition rate and its harmonics of the optical pulse train generated from mode-locked lasers. In our work, instead of using mode-locked lasers as a means of dividing the optical frequency stability of ultrastable optical cavity [13,14], we extracted low phase noise microwave signal directly from sub-femtosecond-jitter mode-locked fiber lasers. By using the sub-100-attosecond jitter Er-fiber lasers [5], we could generate 10-GHz microwave signals with sub-500-attosecond jitter (1 kHz – 10 MHz) and -157 dBc/Hz phase noise at 100 kHz offset frequency [15]. In doing so, the excess noise added in the optical-to-microwave conversion process is minimized by the synchronization between the laser and the microwave source with fiber-loop optical-microwave phase detectors (FLOM-PD) [16]. We showed that ~ -160 dBc/Hz phase noise floor is possible for microwaves directly extracted from 80-MHz fiber lasers.

Precise synchronization between mode-locked lasers and microwave signals is useful for various scientific and engineering applications, such as synchronization for accelerators, ultrafast electron sources, and free-electron lasers. In order to synchronize mode-locked lasers and microwave signals with both sub-fs short-term jitter and sub-fs long-term drift, by using a fiber-loop Sagnac interferometer idea, we developed an all-fiber phase detector that directly detects the phase error between the optical pulse train and the microwave signals, named the FLOM-PD [16]. By using this device, we could show 0.8-fs jitter and drift (over 2 hours) synchronization between an Er-fiber laser and a 10-GHz microwave oscillator. This synchronization technique is used for generating multiple microwave signal sources, tightly locked to

each other, for driving accelerating cavities in free-electron lasers. Recently, the 800-nm version of FLOM-PD has also been used for ultrafast electron sources by synchronizing the optical pulse train from a Ti:sapphire laser and the microwave signal that drives microwave cavity [17]. This will enable to shorten the electron pulse width and also to perform long-term stable pump-probe experiments between optical pump and electron probe signals.

Finally, by using the FLOM-PD as a means for link stabilization, we showed that 2.856-GHz microwave signal transfer over 2.3-km fiber with 6.5×10^{-19} fractional frequency instability [18]. This instability level is the lowest for the microwave transfer over km-scale fiber links, and is limited by the polarization mode dispersion (PMD) of the SMF-28 fiber used, and not by the FLOM-PD performances.

4. Conclusion – Toward attosecond-jitter waveguide lasers

In this paper, I introduced our most recent progress in the development of various types of attosecond-timing-jitter mode-locked fiber lasers and their applications in ultrahigh-precision microwave photonic systems such as microwave synthesis, distribution and synchronization. We are currently working toward implementing attosecond-jitter mode-locked lasers in a fully integrated waveguide device. Passive waveguide components such as WDM coupler, 2x2 coupler, and tunable loop mirror have been recently implemented and tested. Waveguides in active gain section (doped glass) are currently implemented by ion exchange processes and will be tested soon. We anticipate to present the first results of the noise performance of the waveguide mode-locked lasers at the time of conference.

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