Waveform Measurement of Ultra-high Repetition Mode-locked Pulses Generated from a Silica Toroid Microcavity

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A frequency comb, which is a spectrum with broad-bandwidth modes at even intervals in the frequency domain, generates a pulse train with repetition rates of a few terahertz in the time domain. We report that we have obtained pulse trains with 6-7 terahertz repetition rates by measuring the SHG autocorrelation waveform of a Kerr comb generated from an ultra-high Q microcavity. Moreover, we deploy an add/drop system to obtain a higher contrast pulse train, and consider Raman scattering when generating a Kerr comb.

Keywords: frequency comb, NLO, microcavity, ultra-high repetition rates

1. Introduction

A frequency comb, which is a pencil spectrum with modes at even intervals in the frequency domain, is used as a light ruler to obtain accurate wavelength measurements. Expected applications include spectroscopy, optical clocks, GPS, and mass optical communications [1]. Frequency comb sources have included solid-state and fiber lasers. Micro-scale devices make it possible to generate a Kerr comb with lower power [2].

We studied a silica toroid microcavity [3], which has both an ultra-high Q and can be accumulated on chips. Furthermore, we determined whether or not the phases between each mode of the Kerr comb were locked by observing their autocorrelation. A mode-locked Kerr comb is expected to become the next communications light source because it can achieve ultra-high repetition rate pulse trains of over a terahertz. We report the results we obtained observing an ultra-high repetition mode-locked pulse train generated from a silica toroid microcavity.

2. Experiment method

First, we bring a toroid microcavity very close to a tapered fiber, and excitation whispering-gallery modes (WGM) through the near field. A signal from a pump laser operating at a few milliwatts and amplified by an erbium doped fiber amplifier (EDFA) through a tapered fiber is launched into the cavity above the threshold of four wave mixing (FWM) generated by a Kerr comb. When the phase of each Kerr comb mode is aligned, pulses are generated in the cavity. The Kerr comb broadened beyond the C-band in our experiments. Thus, we presume that a few hundred femtosecond, ultra-short Fourier transform limited pulses are generated. We measured the pulses in the time domain with a background-free SHG autocorrelator.

When a tapered fiber is close to the cavity, the Kerr comb generated in it passes to the output. Meanwhile, a pump laser that is not coupled with the cavity and amplified spontaneous emission (ASE) noise produced by an EDFA are also transmitted to the output. This results in output pulses with a lower contrast. Hence, we added another port, called a drop port for the second output in addition to the add port to input the pump laser into the cavity. An add/drop system poses the problem of obtaining lower contrast pulses because of input noise [4]. In this research, we attempted to measure the spectrum and pulse on the add/drop system (Figs.1, 2).

![Fig.1: Photograph of add/drop system. Two fibers are coupled to a silica toroid microcavity.](image1)

![Fig. 2: Scheme of experimental setup. A laser is amplified by an erbium-doped fiber amplifier (EDFA). We measure spectra and pulses not only in the add-side but in the drop side.](image2)

3. Experimental results

First, we measured only the add port. The output from the add port was separated by a 50/50 beam splitter, then each beam was detected with an optical spectrum analyzer (OSA) and an SHG autocorrelator. The spectrum and autocorrelation waves of a Kerr comb from a microcavity are shown in Fig. 3 as an example of input laser detuning. Figure 3 (a-d) show data for the same wavelength. The vertical axis values in Fig. 3 (b) and (d) correspond to each other. The input wavelengths were (a)1546.68 nm, and (c) 1547.61 nm. The input power was 730 milliwatts. The repetition rates, $f_{\text{rep}}$, were (b) 6.22 THz and (d) 7.15 THz. These values correspond to the intervals between the dominant modes: (a) 7-FSR (free spectral range); (b) 8-FSR. The background of the SHG autocorrelation traces in (d) was higher than that in (b) because of the larger timing jitter of the pulses in (d). Actually, the analytics by the split-step Fourier method shows that modulational instability is apparent at a stronger input power [5]. This noise is not attributed to mode locking. Thus, the autocorrelation traces with the 1-FSR interval mode might exhibit less noise. Furthermore, Fig. 3 (a) and (c) show that there is some possibility of dominant 1-FSR interval modes induced by laser detuning in the same way. This corresponds to previously reported simulations [5, 6].
Fig. 3: Spectrum (left) and SHG autocorrelation traces (right) on the add-side.

4. Comparison ADD with DROP

The priority of an add/drop system should be discussed. Using a different cavity from the previous experiment, we compared generated Kerr combs on the add port and on the drop port. Figures 4 and 5 show the OSA spectra on the add side and on the drop side, respectively. First, it is apparent that there was no ASE noise on the drop side. Thus, while a tapered fiber was on the cavity, by accurate coupling, the ASE noise from input would not transmit to the drop port. The margin between the pump line (1549.33 nm) and the dominant comb line a distance of 8-FSR from it is over 20 dBm on the add side, meanwhile it is only 5 dBm on the drop side. This is because the pump line not coupling with the cavity propagates into the output because it is unable to be aligned with accurate critical coupling. On the other hand, because only intracavity modes couple into the output on the drop port, the flat Kerr comb is observed as seen in Fig. 4 (b).

Fig. 4: Kerr comb on the ADD-port (left) and DROP-port (right).

References