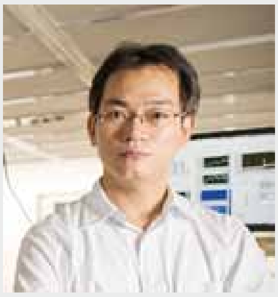
Ultrafast Laser Science

Laser Research Center for Molecular Science
Division of Advanced Laser Development



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Education

1994	B.S. University of Tsukuba
1999	Ph.D. University of Tsukuba

Professional Employment

1999	Assistant Professor, The University of Tokyo
2002	JSPS Postdoctral Fellowship for Research Abroad, Vienna University of Technology (–2004)
2004	Guest Researcher, Max-Planck-Insitute of Quantum Optics
2006	Research Scientist, RIKEN
2008	Senior Scientist, RIKEN
2010	Associate Professor, Institute for Molecular Science Associate Professor, The Graduate University for Advanced Studies

Awards

1999	Encouragement Award, The Optical Society of Japan
2008	Kondo Award, Osaka University

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Light is very common in daily life, on the other hand, light has many interesting physical properties, for example, constancy of velocity, wave-particle duality, *etc*. The study of light is still important in modern physics.

Light is electro-magnetic field, same as radio wave, however, the measurement of the waveform of light is not easy task even in the 21st century. The difficulty comes from the extremely fast oscillation of the light wave. The oscillation frequency of light wave is the order of hundred terahertz (THz = 10^{12} Hz), in other words, the oscillation period of light wave is the order of femtosecond (fs = 10^{-15} s).

In 2013, we have developed a new method for the measurement of light wave. It is called FROG-CEP, frequency-resolved optical gating capable of carrier-envelope phase determination. Our method does not need attosecond pulses, even self-referencing is possible. The electric field oscillation of infrared light with the period of several femtoseconds were clearly measured with the method as is shown in Figure 1.

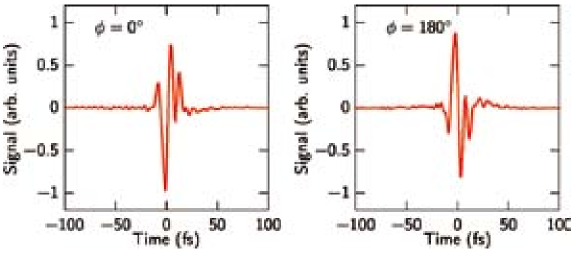

Figure 1. Infrared light waveforms measured with FROG-CEP. The phase difference between the two infrared pulses was clearly measured.

Currently, amplitude modulation and phase modulation are common encoding techniques in optical communication. If we can encode information in the shape of the light wave itself, the communication speed becomes 3 orders of magnitude faster. We believe that our method, FROG-CEP, becomes very important to realize such communication technology.

Other than FROG-CEP, ultrabroadband mid-infrared continuum generation through filamentation and single-shot detection of ultrabroadband mid-infrared spectra have been realized in our laboratory. We are developing such cutting edge technologies for ultrafast laser science.

Selected Publications

- Y. Nomura, H. Shirai, K. Ishii, N. Tsurumachi, A. A. Voronin, A. M. Zheltikov and T. Fuji, "Phase-Stable Sub-Cycle Mid-Infrared Conical Emission from Filamentation in Gases," *Opt. Express* **20**, 24741–24747 (2012).
- T. Fuji and Y. Nomura, "Generation of Phase-Stable Sub-Cycle Mid-Infrared Pulses from Filamentation in Nitrogen," *Appl. Sci.* **3**, 122–138 (2013).
- Y. Nomura, Y. T. Wang, T. Kozai, H. Shirai, A. Yabushita, C. W. Luo, S. Nakanishi and T. Fuji, "Single-Shot Detection of Mid-Infrared Spectra by Chirped-Pulse Upconversion with Four-Wave Difference Frequency Generation in Gases," *Opt. Express* **21**, 18249–18254 (2013).
- T. Fuji, "Single-Shot Broadband Mid-Ir Spectra Measured in the Visible via Upconversion," *Laser Focus World* **49**, 9 (1 page) (2013).
- Y. Nomura, H. Shirai and T. Fuji, "Frequency-Resolved Optical Gating Capable of Carrier-Envelope Phase Determination," *Nat. Commun.* **4**, 2820 (11 pages) (2013).

1. Frequency-Resolved Optical Gating Capable of Carrier-Envelope Phase Determination (FROG-CEP)[1,2]

Recent progress of the coherent light synthesis technology has brought the generation of single-cycle pulses within our reach. To exploit the full potential of such a single-cycle pulse in any applications, it is highly important to obtain the full information of its electric field.

There has been a method to measure the oscillation of light wave using attosecond (as = 10^{-18} s) pulses (attosecond streaking, [*Science* **305**, 1257]), however, a huge high vacuum system is necessary for the measurement since attosecond pulses, which are in XUV region, are absorbed in air.

Here, we propose a novel pulse characterization scheme, which enables us to determine not only the intensity and phase profiles of ultrashort pulses but also their absolute carrier-envelope phase values without using attosecond pulses. The method is based on a combination of frequency-resolved optical gating and electro-optic sampling.

We have demonstrated the method by characterizing phase-stable sub-single-cycle 7 fs infrared pulses generated through filamentation[3,4] by using a 30 fs reference pulse, which is much longer than the period of the carrier-wavelength of the characterized pulse. We have also demonstrated that the method has the capability of single-shot measurements. The self-referencing possibility of the method has been also discussed with numerical simulations. The results of our numerical simulations have clearly shown that it is possible to retrieve few-cycle 800 nm pulses with the absolute CEP information by self-referencing. It has turned out that approximately one octave spectrum and reasonable compression quality are necessary for the self-referencing, which is rather reasonable requirement for the waveform characterization of few-cycle pulses whose CEP becomes important. In principle, the concept has no limitation to characterize few-cycle pulses on measurable pulse duration or applicable wavelength regions thanks to the self-referencing possibility.

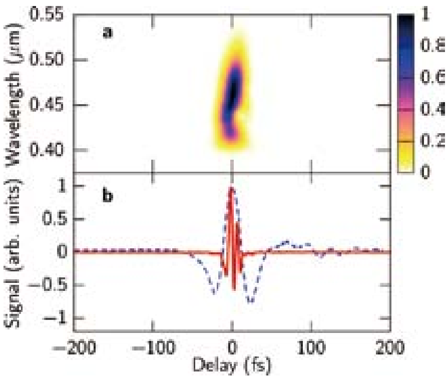

Figure 2. Experimental results of FROG-CEP. (a) The XFROG trace and (b) EOS signal measured in the experiment (blue dashed curve). The red solid curve shows the electric field reconstructed from the experimental data.

2. Sub-50-fs Pulse Generation from Thulium-Doped ZBLAN Fiber Laser Oscillator[5]

Passively mode-locked fiber lasers operating around 1 μm and 1.5 μm have been extensively studied over the past decades. In recent years, thulium-doped fiber lasers have attracted significant attention because they extend the operating wavelength toward 2 μm region, which will be useful for various fields such as medical applications, remote sensing, micromachining, high harmonic generation, and mid-infrared generation. In particular, broad emission spectra of thulium-doped fibers make them ideal candidates for ultrashort pulse sources in this wavelength region. However, it is not trivial to obtain ultrashort pulses from fiber lasers where the effect of the dispersion from long fibers is quite significant.

An interesting approach would be using fibers made of materials with less dispersion. Fluoride glass known as ZBLAN (ZrF_4–BaF_2-LaF_3-AlF_3-NaF) has high transmittance in the mid-infrared region. The property of low absorption suggests that it also has low dispersion in the mid-infrared region. However, the property has been overlooked and no previous work has utilized ZBLAN fibers for developing ultrafast laser oscillators.

In this work, we have developed a passively mode-locked laser oscillator based on thulium-doped ZBLAN fibers pumped by a cw Ti:sapphire laser. Output pulses with the average power of 13 mW are obtained at the repetition rate of 67.5 MHz with the pump power of 140 mW. Thanks to low dispersion of ZBLAN, the spectra of the output beam was as broad as 300 nm at 30 dB below the peak. The generated pulses was compressed down to 45 fs, which is the shortest pulses generated from laser oscillators operating around 2 μm wavelength region to the best of our knowledge.

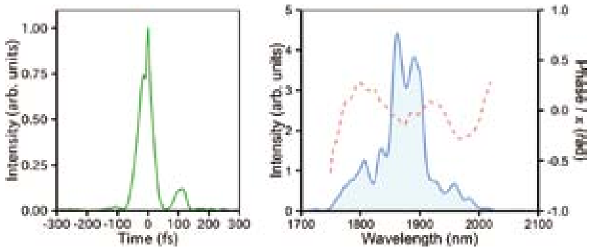

Figure 3. Measured pulse shape (Left). Measured spectral profile (Right, filled blue curve) and phase (Right, dashed red curve).

References

1) Y. Nomura, H. Shirai and T. Fuji, *Nat. Commun.* **4**, 2820 (2013).
2) H. Shirai, Y. Nomura and T. Fuji, *IEEE Photonics J*. **6**, 3300212 (2014).
3) Y. Nomura, H. Shirai, K. Ishii, N. Tsurumachi, A. A. Voronin, A. M. Zheltikov and T. Fuji, *Opt. Express* **20**, 24741–24747 (2012).
4) T. Fuji and Y. Nomura, *Appl. Sci.* **3**, 122–138 (2013).
5) Y. Nomura and T. Fuji, *Opt. Express* **22**, 12461–12466 (2014).

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* EXODASS Program
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