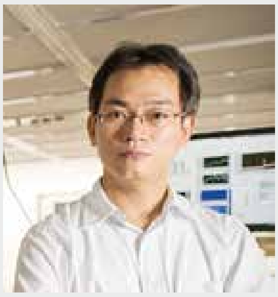
Ultrafast Laser Science

Center for Mesoscopic Sciences
Division of Broadband Multiscale Analysis



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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

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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 itself 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 determination. Our method does not need attosecond pulses, even self-referencing is possible. The electric field oscillations of infrared light with the period of several femtoseconds were clearly measured with the method as is shown in Figure 1.

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.

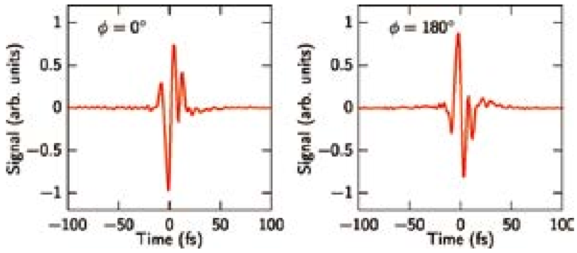

Figure 1. Infrared light waveforms measured with FROG-CEP. The phase difference between the two infrared pulses was clearly measured.

Other than FROG-CEP, ultrabroadband mid-infrared continuum generation through filamentation, single-shot detection of ultrabroadband mid-infrared spectra, and development of 2 μm ultrafast lasers have been realized in our laboratory. We are developing such cutting edge technologies for ultrafast laser science.

Selected Publications

- 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, H. Shirai and T. Fuji, "Frequency-Resolved Optical Gating Capable of Carrier-Envelope Phase Determination," *Nat. Commun.* **4**, 2820 (11 pages) (2013).
- Y. Nomura M. Nishio, S. Kawato and T. Fuji, "Development of Ultrafast Laser Oscillators Based on Thulium-Doped ZBLAN Fibers," *IEEE J. Sel. Top. Quantum Electron.* **21**, 0900107 (7 pages) (2015).
- T. Fuji, Y. Nomura and H. Shirai, "Generation and Characterization of Phase-Stable Sub-Single-Cycle Pulses at 3000 cm^{-1}," *IEEE J. Sel. Top. Quantum Electron.* **21**, 8700612 (12 pages) (2015).
- T. Fuji, H. Shirai and Y. Nomura, "Ultrabroadband Mid-Infrared Spectroscopy with Four-Wave Difference Frequency Generation," *J. Opt.* **17**, 094004 (9 pages) (2015).
- H. Shirai, Y. Nomura and T. Fuji, "Self-Referenced Measurement of Light Waves," *Laser Photonics Rev.* **11**, 1600244 (6 pages) (2017).

1. High Harmonic Generation in Solids Driven by Sub-Cycle Mid-Infrared Pulses from Two-Color Filamentation

High-harmonic generation (HHG) is one of the most important nonlinear processes for the generation of attosecond pulses. In the last few years, HHG in solid materials is attracting a lot of attention in the fields of ultrafast science and solid-state physics. Since the atomic density is much higher in solids than in gases, solid-state HHG would be much more efficient than the HHG in atomic gases. The solid-state HHG would be a key technology to realize a compact solid-state attosecond pulse generator or petahertz electronics.

Naturally, experimental study with well-characterized single-cycle or sub-cycle pulses is one of the most straightforward approaches to investigate highly nonlinear process. Here, we report the demonstration of the HHG in a Si membrane driven by carrier-envelope phase (CEP) controlled sub-cycle mid-infrared (MIR) pulses generated through two-color filamentation.

The light source was based on a Ti:Sapphire multipass amplifier system. The generation scheme of the sub-cycle MIR pulses is the same as that published before.[1,2] In brief, the fundamental (800 nm, ω_1) and second-harmonic (400 nm, ω_2) pulses were gently focused into nitrogen, in which the sub-cycle MIR pulse (ω_0) was generated by using four-wave mixing ($\omega_1 + \omega_1 - \omega_2 \rightarrow \omega_0$) through filamentation. As is the case with the difference frequency generation, the CEP of the MIR pulse is passively stabilized.

Figure 2(a) shows a typical power spectrum and (absolute) spectral phases of the MIR pulses obtained with FROG-CEP measurements.[3] The spectrum covers the entire MIR region, corresponding to more than three octaves, and the spectral phase has some nonlinear term; namely, the pulse is slightly chirped. The pulse duration of the MIR pulse is estimated as ~8.5 fs at FWHM, corresponding to 0.64 optical cycles at 4 μm center wavelength. The waveforms of MIR pulses for the phases of -0.10π and -0.77π at 4 μm are shown in Figure 2(b). We can control the CEP of the MIR pulse very precisely by tilting the delay plate on a kinematic mount with a piezoelectric inertia actuator.

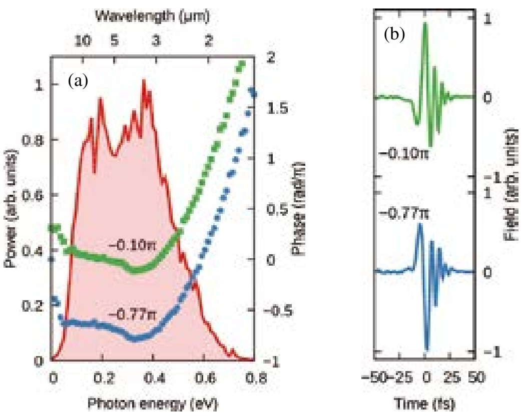

Figure 2. a) Power spectrum (shaded curve) and (absolute) spectral phases (closed circles and squares) of the MIR pulses obtained with the FROG-CEP technique. (b) Retrieved waveforms of the MIR pulses.

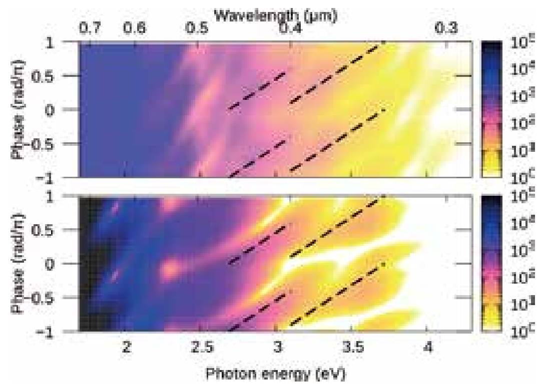

Figure 3. CEP dependence of the HH spectrum. (a) Experimental result. (b) Numerical simulation result obtained from optical Bloch equations.

Figure 3(a) shows the CEP dependence of the high-harmonic (HH) spectrum. We continuously recorded the HH spectra while scanning the CEP from $-\pi$ to π. The HH spectra reach <300 nm, the ultraviolet region. The spectrum shifts to the higher photon energy region by increasing the CEP (indicated by dotted lines), and the same spectrum appears every π phase shift.

To investigate the complex structure and CEP dependence of the HH spectrum, we numerically simulated the CEP dependence of the HH spectrum based on the optical Bloch equations generalized to the case of a two-band semiconductor. In this numerical simulation, we used the waveform of the sub-cycle MIR pulse measured with FROG-CEP as a driving field.

Figure 3(b) shows the simulation result of the CEP dependence of the HH spectrum. As is the case with the experimental results in Figure 3(a), the spectral shape shifts to a higher photon energy region by increasing the CEP of the MIR pulse, and the same spectrum appears at every π phase shift. In addition, discontinuous change of the CEP dependence of the HH spectrum at around 3.1 eV, which corresponds to the direct band gap energy, is also reproduced [see dashed lines in Figures 3(a) and 3(b)]. We believe that the CEP dependence change is due to the increase in the imaginary part of the refractive index at around the direct band gap. In this simulation, the main features of the experimental result are qualitatively reproduced.

References

1) T. Fuji and Y. Nomura, *Appl. Sci.* **3**, 122 (2013).
2) T. Fuji, Y. Nomura and H. Shirai, *IEEE J. Sel. Top. Quantum Electron.* **21**, 8700612 (2015).
3) Y. Nomura, H. Shirai and T. Fuji, *Nat. Commun.* **4**, 2820 (2013).

* IMS International Internship Program
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