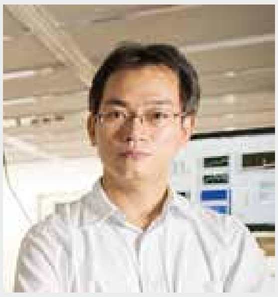
Ultrafast Laser Science

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
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1999 Encouragement Award, The Optical Society of Japan
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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 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.

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.

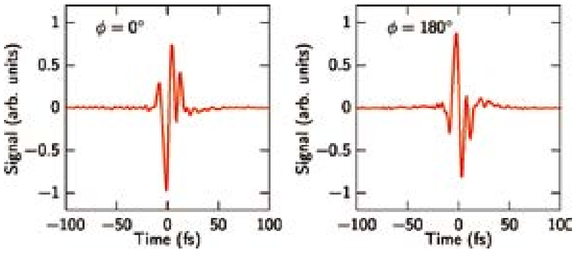

Figure 1. Infrared light waveforms measured with FROG-CEP. The phase difference between the two infrared pulses was clearly measured.

Other than FROG-CEP, ultrabroadband mid-infrared continuum generation through filamentation and single-shot detection of ultrabroadband mid-infrared spectra has 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).
- Y. Nomura, Y.-T. Wang, A. Yabushita, C.-W. Luo and T. Fuji, "Controlling the Carrier-Envelope Phase of Single-Cycle Mid-Infrared Pulses with Two-Color Filamentation," *Opt. Lett.* **40**, 423–426 (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).

Ultrafast lasers working in the 2 µm region have been attracting a lot of attention owing to a number of possible applications in various scientific and industrial fields. Thulium (Tm)-doped fiber or solid-state lasers are one of the most promising candidates to generate ultrashort pulses in this wavelength region because of their broad emission spectra. We have developed an oscillator based on a Tm-doped ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) fiber which delivers 41 fs pulses at 2 µm.[1,2] Here we report the development of the amplifier for the oscillator output.

1. Chirped-Pulse Amplifier Based on Thulium-Doped ZBLAN Fibers

ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) is fluoride glass known for high transmittance in the mid-infrared region. This suggests the ZBLAN glass has low material dispersion, which fact would be suitable for ultrafast amplifier system.

Here we demonstrate a chirped-pulse amplifier (CPA) system based on ZBLAN fibers. The experimental setup consists of an oscillator, a stretcher, an amplifier, and a compressor. The pulses from the oscillator are stretched with a normal-dispersion ZBLAN fiber with the core diameter of 5 µm (group velocity dispersion ~+30 fs^2/mm). After propagating through the 15-m-long ZBLAN fiber, the pulses are stretched to ~25 ps with ~50% transmission efficiency. After all the optics, the average power of the stretched pulses is 12 mW.

The stretched pulses are sent into the core of a 3.8-m-long, Tm-doped, large-mode-area double-clad ZBLAN fiber. The core of the fiber has a diameter of 32 µm and NA of 0.08, whereas the first clad has a diameter of 200 µm and NA of 0.5. The concentration of Tm ion in the core is 2 mol%.

The fiber is pumped in the counter-propagating direction, *i.e.*, from the side of the non-doped fiber, with a laser diode (LD) operating around 793 nm. When the output power of the LD is increased to 20 W, the maximum output power of 4.5 W is obtained. The slope efficiency is ~29% if we assume the pump coupling efficiency to be 90%.

Figure 1(a) shows the spectrum of the amplifier output, extending over more than 100 nm. This value is much less compared to the oscillator spectral width of 350 nm, which could be explained by gain narrowing effect and strong absorption of Tm ion in the short wavelength region.

The amplified pulses are compressed with a compressor comprised of a pair of transmission grating with grooves of 560 mm^{-1}. The average power after the compressor is 2.5 W. The compressed pulses are characterized with a home-built frequency-resolved optical gating (FROG) device designed for pulses around 2 µm region. A typical FROG trace and the pulse retrieved from it are shown in Figure 1(b) and (c). From this result, the duration of the compressed pulse is determined as 150 fs.

2. Ring Cavity Diode-Pumped Tm:YAP Regenerative Amplifier

To obtain higher pulse energy, we have developed an amplifier based on a solid-state laser, namely, diode pumped Tm:YAP regenerative amplifier.

The CPA system consists of a Tm:ZBLAN fiber oscillator, grating stretcher, ring-cavity regenerative amplifier and grating compressor. The Regenerative amplifier is based on Brewster- cut 4% doped 12 mm long 6.5 °C water cooled Tm:YAP crystal end-pumped by 794 nm InGaAs diodes, being reimaged into 400 µm spot on the crystal. The CPA system is seeded by 90 fs 52 MHz 4 nJ Tm:ZBLAN fiber oscillator. The seed pulses are sent to the Martinez type stretcher based on a 550 gr/mm transmissive grating and concave mirror with the group delay dispersion of 16 ps^2, which is necessary to avoid damage and non-linear effects while operating at high energies. The regenerative amplifier generates >0.9 mJ pulses at 1 kHz repetition rate, or, by decreasing repetition rate to 250 Hz, it is possible to extract up to 2.0 mJ pulses.

Even though the cavity is nitrogen purged (to 9% residual humidity level), the high water vapor absorption leads to generation of strongly modulated spectrum. Measured spectrum supports 0.46 ps duration, but recompression with 560 gr/mm gratings Treacy compressor results in autocorrelation of 1 ps spike with strong 10^s ps long pedestal, which can be cleaned out by stronger dehumidifying.

References

1) Y. Nomura and T. Fuji, *Opt. Express* **22**, 12461–12466 (2014).

2) Y. Nomura, M. Nishio, S. Kawato and T. Fuji, *IEEE J. Sel. Top. Quantum Electron.* **21**, 0900107 (2015).

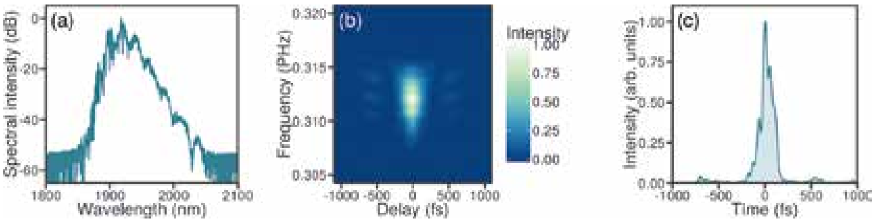

Figure 2. Output after amplification. (a) An output spectrum after the amplifier. (b) A FROG trace measured after compression. (c) The pulse shape retrieved from the FROG trace shown in (b).

Award

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