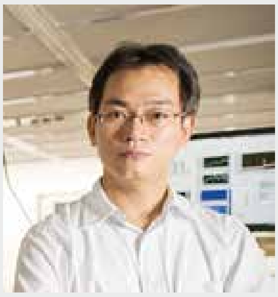
Ultrafast Laser Science

Center for Mesoscopic Sciences
Division of Broadband Multiscale Analysis



FUJI, Takao
Associate Professor
(–March, 2019)
[fuji@ims.ac.jp]

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
2019 Professor, Toyota Technological Institute

Awards

1999 Encouragement Award, The Optical Society of Japan
2008 Kondo Award, Osaka University
2015 Laser Research Development Award, the Laser Society of Japan

Member

Assistant Professor
NOMURA, Yutaka
IMS Fellow
REZVANI, Seyed Ali
Visiting Scientist
HUANG, Wei-Hong
Graduate Student
KUMAKI, Fumitoshi
ITOH, Takuma*
Secretary
MASUDA, Michiko

Keywords Ultrafast Science, Laser Physics, Nonlinear Optics

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.

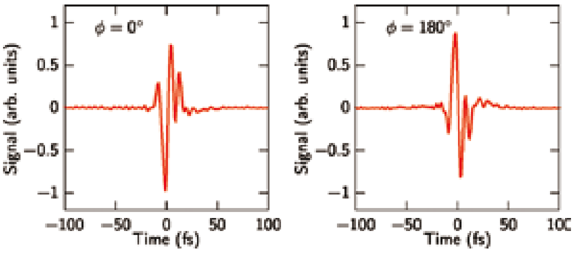


Figure 1. Infrared light waveforms measured with FROG-CEP. The phase difference between the two infrared pulses was clearly measured.

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

- 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).
- H. Shirai, Y. Nomura and T. Fuji, “Self-Referenced Measurement of Light Waves,” *Laser Photonics Rev.* **11**, 1600244 (6 pages) (2017).
- S. A. Rezvani, M. Suzuki, P. Malevich, C. Livache, J. V. de Montgolfier, Y. Nomura, N. Tsurumachi, A. Baltuska and T. Fuji, “Millijoule Femtosecond Pulses at 1937 nm from a Diode-Pumped Ring Cavity Tm:YAP Regenerative Amplifier,” *Opt. Express* **26**, 29460–29470 (2018).

1. Development of Intense Femtosecond Lasers at 2 μm1)

Intense ultrashort infrared pulse lasers are highly attractive in many research fields. Powerful femtosecond pulses in the vicinity of 2 μm are desired for coherent mid-infrared or terahertz pulse generation, high harmonic generation in the water window soft x-ray region, and atmospheric sensing. In order to obtain intense femtosecond pulses around the 2 μm wavelength region, one of the most widely used schemes is optical parametric amplification (OPA) with well-established ultrafast pump lasers such as Ti:sapphire or Yb lasers. However, OPA in general has a complicated design due to the requirement of the precise synchronization between the pump and seed pulses. This fact attracts a lot of attention to the development of solid-state lasers which directly generate high energy ultrashort pulses around 2 μm.

In this work we present a new table-top Tm:YAP laser system based on a diode-pumped ring cavity regenerative amplifier. The system generates 360 fs pulses at 2 μm with the peak power of 2 GW after the compression.

The schematic of the system is shown in Figure 2. The seed source of the laser system is a Tm:ZBLAN fiber oscillator,2) which generates 2 μm pulses with the pulse energy of 4 nJ. The pulses are sent to a grating stretcher and then to a ZBLAN fiber pre-amplifier pumped by a laser diode at 794 nm.3)

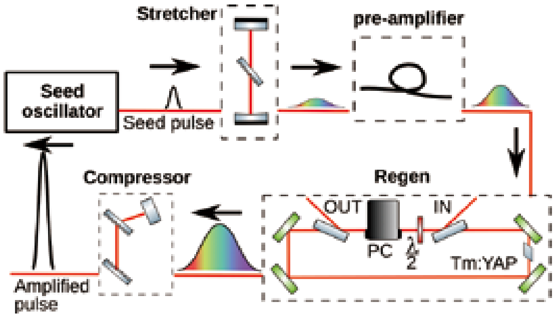


Figure 2. Schematic of the system. PC: Pockels cells.

The amplified seed pulses (~100 nJ) are picked with 1 kHz rate by a Pockel cell and are sent to a regenerative amplifier based on a Brewster-cut, 4% doped, 12 mm long Tm:YAP crystal which is pumped by another 794 nm laser diode. The output power of the regenerative amplifier is 1.4 W with the absorbed pump power is 23.5 W at 45 round trips. The output pulse is compressed using a pair of gratings. The energy of the compressed pulse is 0.924 mJ.

The compressed pulse was characterized using a home-built SHG-FROG system. The temporal and spectral profile of the pulse obtained by the system are shown in Figure 3. The pulse duration is 360 fs.

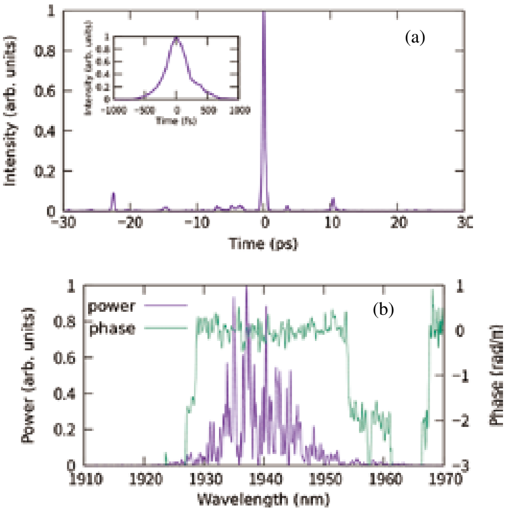


Figure 3. (a) Temporal profile of the pulse from the amplifier. Inset: Zoomed view of the main pulse peak. (b) Power spectrum and spectral phase of the pulse.

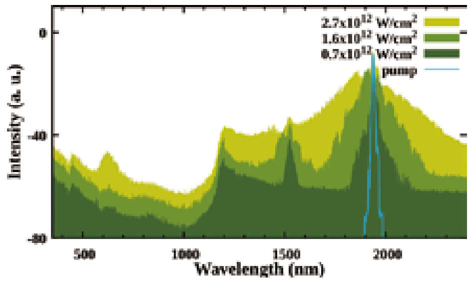


Figure 4. Variation of the generated white light with the changes of the pump intensity.

The compressed pulses exhibit good beam profile and can be directly used to generate white light in bulk materials. Using only 15 μJ of the amplified pulse, we have generated white light in a 3 mm YAG crystal. The white light spectra are shown in Figure 4.

Such properties combined with the good power scalability over a wide range of available pumping energies makes this scheme a viable candidate for direct application for mid-infrared OPA. In particular, the system exhibits a flexible electronic control on the obtainable output energy through changes in round trips, pumping energy, and repetition rate. The feature makes it a good candidate for many applications such as spectroscopy which would require a tight control over the light source. The proposed ring regenerative amplifier provides a versatile and simple infrared source that can be used in many of the current applications, in a compact table-top design.

References

1) S. A. Rezvani, M. Suzuki, P. Malevich, C. Livache, J. V. de Montgolfier, Y. Nomura, N. Tsurumachi, A. Baltuska and T. Fuji, *Opt. Express* **26**, 29460 (2018).
2) Y. Nomura, M. Nishio, S. Kawato and T. Fuji, *IEEE J. Sel. Top. Quantum Electron.* **21**, 0900107 (2015).
3) Y. Nomura and T. Fuji, *Appl. Phys. Express* **10**, 012703 (2016).

---

* carrying out graduate research on Cooperative Education Program of IMS with Kagawa University