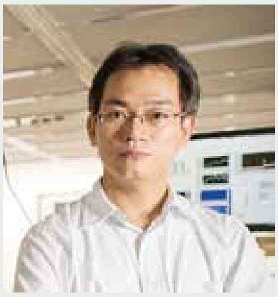
Ultrafast Laser Science

Center for Mesoscopic Sciences
Division of Broadband Multiscale Analysis



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Professional Employment
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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.

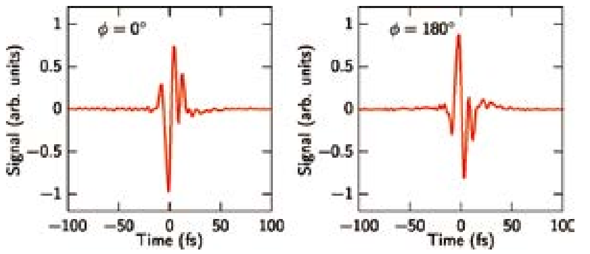

Figure 1. Infrared light waveforms measured with FROG-CEP. The phase difference between the two infrared pulses was clearly measured.

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. Self-Referenced Waveform Measurement of Ultrashort Pulses

As is written in the previous page, it is still very difficult to directly sample an optical field transient on a time scale below the oscillation period. It has been naturally believed that the field oscillation can be detected only by using a reference pulse that has a shorter duration than the period of the oscillation.

In 2013, we proposed a new scheme of waveform characterization, frequency-resolved optical gating capable of carrier-envelope phase determination (FROG-CEP),[1] which is based on a combination of frequency-resolved optical gating (FROG) with a carrier-envelope phase (CEP) sensitive time-domain nonlinear interferometer. The intensity and relative spectral phase of the target pulse are obtained from the FROG measurement, and the CEP is obtained from the nonlinear interferometer. Combining these data sets, we are able to retrieve a complete waveform of the target pulse. In this method, it is possible to measure a waveform with a reference pulse that has a longer duration than the period of the target pulse. The fact suggests that self-referenced waveform characterization is possible by using FROG-CEP.

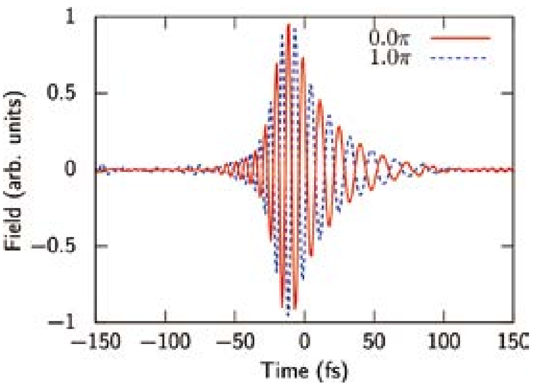

Figure 2. Retrieved electric-field in time domain. The solid line is the electric-field reconstructed with the method described in the text. The dotted line is the electric field where the CEP of the pulse is experimentally changed by π.

Here, we show the experimental demonstration of self-referenced FROG-CEP for few-cycle MIR pulses.[2] We simultaneously measured a trace of second harmonic generation FROG (SHG-FROG) and interferogram between second harmonic (SH) and self-diffraction (SD) signals. The intensity and relative spectral phase of the target pulse are obtained from SHG-FROG, and the CEP is obtained from the interferogram. The retrieved waveform is shown in Figure 1.

2. Direct Amplification of 2 μm Femtosecond Pulses in a Tm:ZBLAN Fiber

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 lasers are one of the most promising candidates to generate ultrashort pulses in this wavelength region because of their broad emission spectra. Here we report the development of a fiber amplifier.

To develop high power, femtosecond light sources at the 2 μm region, the most straightforward method is the chirped-pulse amplification (CPA) technique. Another approach to build an ultrafast fiber laser amplifier is to make use of the nonlinearity within the fiber to broaden the spectrum rather than suppressing the nonlinearity. This approach was successful especially for developing ultrafast ytterbium-doped fiber laser amplifiers. However, the situation is quite different for Tm-doped fiber lasers because the fibers have anomalous dispersion around 2 μm region and thus the nonlinearity during amplification leads to wave breaking, which is usually considered detrimental.

We demonstrate direct generation of sub-50 fs pulses from a Tm-based fiber amplifier by utilizing nonlinearities within the amplifier fiber itself. Pulses with a duration of 48 fs are obtained at an average power of 2.5 W. The core-pumping scheme helped to obtain broad spectra extending into relatively short wavelength region around 1.7 μm. The setup uses no stretcher or compressor, resulting in an extremely simple system.[3]

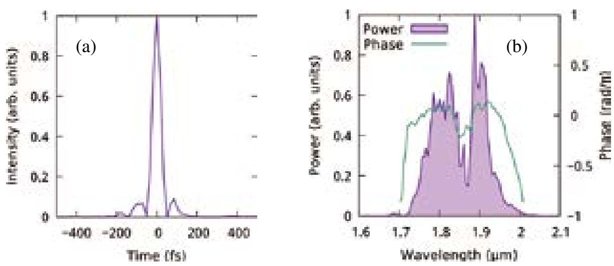

Figure 3. (a) Pulse shape retrieved from the FROG measurement. (b) Spectral intensity (blue solid curve) and phase (green dashed curve) profiles retrieved from the FROG measurement.

Figure 3 summarizes the results of FROG measurements of the amplified pulse. The pulse shape retrieved from the FROG measurement is shown in Figure 3(a). The duration of the pulse is as short as 48 fs, which is only 7% above the transform limit duration of 45 fs. The spectral intensity and phase profiles retrieved from the same FROG trace are shown in Figure 3(b). It can be seen that the phase is more or less flat for the main parts of the spectrum, whereas distorted in the region where the spectral intensity is relatively low.

References

1) Y. Nomura, H. Shirai and T. Fuji, *Nat. Commun.* **4**, 2820 (2013).
2) H. Shirai, Y. Nomura and T. Fuji, *Laser Photonics Rev.* **11**, 1600244 (2017).
3) Y. Nomura and T. Fuji, *Opt. Express* **25**, 13691 (2017).