

# Advanced Energy Conversion Division

## Advanced Energy Transportation Research Section

K.Miyazaki, Professor

T.Nakajima, Associate Professor

K.Hata, Research Associate

### 1. Introduction

The research interests of this section are focused on the development of advanced lasers and their application to the study of laser interactions with matter. The current research subjects in the laser development are concerned with the generation of high-intensity ultrashort pulses. The high-intensity laser which produces ultrashort pulses of fsec to psec durations has been opening new fields of science and technology, providing an increasingly important scientific tool in the extremely-ultrashort time and/or strong-field regimes to which one could never approach so far.

We have developed a fsec, high-intensity Ti:sapphire laser system using the chirped-pulse amplification (CPA) technique, which is capable of producing a peak power of 1 TW in 40 fsec pulses. The output of this laser system has been frequency converted to produce fsec, high-intensity laser pulses in short-wavelength spectral regions. Another high-intensity laser system under development is a compact, broadly tunable, ultrashort-pulse laser based on Nd:YVO<sub>4</sub> and Nd:YAG lasers. These lasers are applied to the study of strong-field interactions with atoms, molecules and solid surfaces; e.g., high-order harmonic generation in gaseous media, field ionization of atoms and molecules, and ultrafast ablation processes on various kinds of materials.

This research section is also working on the fundamental study of steady and unsteady heat and fluid flow in water, cryogenic liquids and liquid metals, in cooperation with several groups to provide database for nuclear fusion test facilities and future fusion reactors.

### 2. High-intensity lasers

#### 2.1 Ultrashort-pulse Ti:sapphire laser

The CPA laser system developed consists of a mode-locked Ti:sapphire laser oscillator pumped by the second harmonic output of an all solid-state Nd:YVO<sub>4</sub> laser, an all-reflective pulse expander, three Ti:sapphire amplifiers pumped by a frequency-doubled Nd:YAG laser, and a grating pulse compressor. The mode-locked oscillator continuously pumped by the green laser output of 4.3 W produces an average power of 450 mW at a repetition rate of 80 MHz. The oscillator output is usually fixed at the center wavelength of 795 nm with a bandwidth of about 45 nm, and the pulse width is 30 fsec. The 30-fsec pulses are stretched to a width of 250 psec by the pulse stretcher consisting of two 1200-grooved/mm gold-coated gratings and two cylindrical mirrors. The chirped pulses from the stretcher are sent to the multi-stage amplifiers pumped by the 800-mJ, 532-nm Nd:YAG laser pulses at a repetition rate of 10 Hz. A single chirped pulse of about 0.2 nJ is selected in the first regenerative amplifier and amplified up to a pulse energy of 3 mJ. The second and third double-pass power amplifiers increase the chirped-pulse energy up to 13 mJ and to 80 mJ, respectively. The output from the third amplifier is collimated to ~ 20 mm in diameter with a lens telescope and sent to the double-pass compressor consisting of two 1200-grooved/mm gold-coated gratings and a roof mirror. The transmission of the compressor is about 50 %, producing the compressed pulse energy of 40 mJ.

The spectral peak of the amplified and compressed output is slightly shifted to a red spectral region around 800 nm. The compressed

pulse width was 40 fsec, which was measured with a single-shot autocorrelator. Thus, the laser system can produce a peak power of about 1 TW at a repetition rate of 10 Hz. The shot-by-shot fluctuation of the output pulse energy and pulse width was less than 5 %. The fsec high-intensity pulse could easily produce white-light continuum in air when it was focused. The continuum generation in air has been conveniently used to make the initial adjustment of the grating separation in everyday operation.

## 2.2 Broadly-tunable psec laser

For the generation of broadly-tunable, high-intensity ultrashort pulses, we are developing a psec laser system for optical parametric generation (OPG) and amplification (OPA) using nonlinear optical crystals. The OPG and OPA system is pumped by the third harmonic (355 nm) of a psec high-intensity Nd:YAG laser. In the pump laser system, the seed psec pulses at 1064 nm are produced by a cw mode-locked Nd:YVO<sub>4</sub> laser using a semiconductor saturable-absorber mirror (SESAM) for stable passive mode locking. The mode-locked, 100-mW output is sent to a fiber transmission line, and the fiber output of about 30 mW is injected into a flash-lamp-pumped regenerative Nd:YAG amplifier operating at a repetition rate of 10 Hz. A single amplified pulse is selected and further amplified by a Nd:YAG power amplifier. The output pulse energy at 1064 nm is about 70 mJ in 40 psec pulses. The fundamental is frequency doubled and tripled by KD\*P crystals, and the second and third harmonic pulse energy is about 15 mJ and 6.5 mJ, respectively. The third-harmonic (TH) pulse width at 355 nm is expected to be 20 - 25 psec.

After the pulse energy is controlled by a set of a half-wave plate and a polarizer, the TH pulse at 355 nm is focused by a pair of positive and negative lenses to a beam of about 2 mm in diameter. This collimated ultraviolet (UV) beam pumps two LBO crystals both of which are cut at  $\theta = 90^\circ$  and  $\phi = 29^\circ$  for type-I phase matching. The LBO crystals are 10 mm and 15 mm in length for the OPG and OPA, respectively. The observed OPA output was tunable in a spectral range from 405 nm to 2000 nm.

## 3. Frequency conversion

### 3.1 High-intensity, fsec blue and UV pulses

Current technology for the generation of high-intensity ultrashort pulses is based on Ti:sapphire lasers, and the output spectra of useful high-intensity lasers are limited to a wavelength region of 800 nm. The extension of this spectral region of high-intensity lasers is an urgent subject for both academic and application purposes. One of the most convenient methods to extend the laser spectrum is the frequency conversion in a nonlinear crystal. However, the frequency conversion of high-intensity ultrashort pulses meets some difficulties that arise from the ultrashort pulses and the high intensity. The problems are concerned with 1) phase matching for the broad spectra of ultrashort pulses, 2) group-velocity mismatching (GVM) between the fundamental and frequency-converted fields in a nonlinear crystal, and 3) additional nonlinear effects induced at the high intensity. Of these, the GVM should be the main limitation to the efficient conversion without a dramatic pulse broadening. For example, the GVM between the fundamental at 800 nm and the SH in the weak-pumping regime is estimated to be 194 fsec/mm for BBO crystal and 77 fsec/mm for KDP crystal. Therefore, a very thin nonlinear crystal has to be used to maintain the ultrashort pulse width in the frequency conversion.

The second harmonic generation (SHG) and successive third-harmonic generation (THG) was done by using BBO crystals cut for type-I phase matching. Throughout the experiments, the largest beam diameter of the 40-fsec fundamental pulse was 15 mm. This diameter was limited by the size of the commercially available thin BBO crystal. The fundamental pulse was frequency doubled in a 0.2-mm thick BBO crystal. Even in such a thin BBO crystal, the SH pulse at 400 nm was observed to be delayed from the fundamental at the BBO end surface. For compensating the time delay between the fundamental and SH pulses, a thin (1.6 - 2.0 mm) calcite crystal was placed behind the SH crystal. The calcite crystal is cut at  $43.5^\circ$  against the  $z$  axis, and then the fundamental and SH pulses travel through the birefringent crystal and experience different

refractive indexes to recover the time delay. This technique for compensation of a time delay maintained a good spatial overlap of two beams for the subsequent THG. The waveplate set behind the calcite plate rotates the fundamental and SH polarization so that two beams have an identical polarization direction for type-I THG. A 0.3-mm thick BBO crystal was used for the THG. The crystal thickness was not optimized to obtain the shortest TH pulse. The calculated GVM in the THG is 327 fsec/mm for the  $\omega$  and  $2\omega$  pulses, 737 fsec/mm for  $\omega - 3\omega$ , and 410 fsec/mm for  $2\omega - 3\omega$ . This suggests that one has to use a very thin BBO for eliminating an appreciable pulse broadening in the THG, whereas the conversion efficiency must be very low.

The measured conversion efficiency and harmonic pulse energy are plotted in Fig.1, where the maximum fundamental intensity at the SHG crystal was about  $500 \text{ GW/cm}^2$ . The highest SH conversion efficiency is more than 40 %, and the pulse energy produced at 400 nm is more than 10 mJ. In the THG, the maximum conversion efficiency of about 15 % is observed with the pulse energy of about 2 mJ at 266 nm. The  $(\omega + 2\omega)$  pulse energy at the THG crystal was greatly decreased by the multiple reflections at the uncoated calcite and waveplate surfaces.

The cross correlation measurement were made to estimate the SH and TH pulse widths. Figure 2 shows the measured pulse width as a function of the fundamental (800 nm) intensity used. The SH pulse width is 60 - 80 fsec, while the TH pulse width is stretched to 100 - 150 fsec. The pulse broadening is due mainly to the GVM, especially for the TH pulse. In addition, saturation of SHG and THG at the high fundamental intensity would lead to the pulse broadening. We observed some spectral shift in the frequency conversion due most probably to the self-phase modulation (SPM) of the laser pulses. The peak power of an ultrashort blue (400 nm) pulse is about 0.1 TW, and that of an ultraviolet (267 nm) pulse is about 10 GW.

### 3.2. High-field Interactions

One of the most interesting applications of high-intensity ultrashort laser pulses is the generation of high-order harmonics in a gaseous

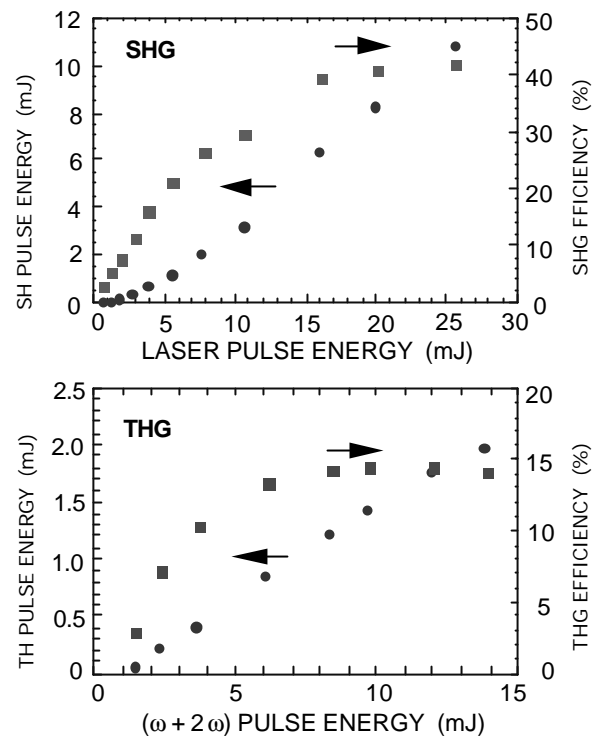


Fig.1. SH and TH pulse energy and conversion efficiency as a function of fundamental energy. Beam diameter: 15 mm.

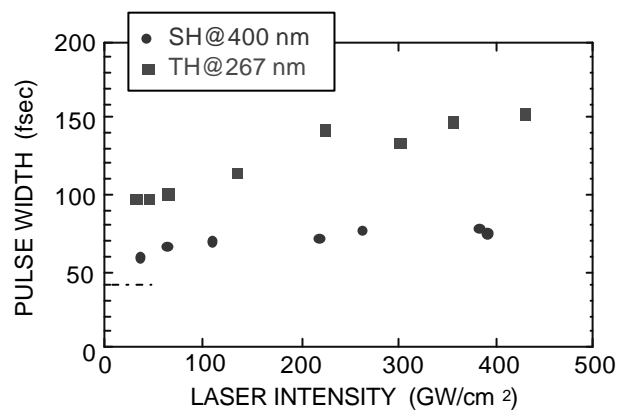


Fig.2. SH and TH pulse widths as a function of laser intensity.

medium. The high-order harmonic generation (HHG) provides a promising approach to develop a compact, high-brightness coherent soft X-ray source. One of the most important problems is phase matching or improvement of conversion efficiency in the HHG process. The phase-matching problem arises from the propagation of a ultrashort laser pulse in a dispersive high-density gaseous medium and also from the intrinsic phase change of an electron in the single

atom response. We have been developing an experimental apparatus to study the detailed interaction processes in a high-density medium, and a time-of-flight apparatus is also under development to study the single atom response in the high field.

#### 4. Phase control

One of the ways of controlling the light-matter interaction is to manipulate the phase of lasers, by which a destructive or constructive interference is induced between different transition paths to the same final state. Experimentally this is often realized using a fundamental and its third ( $\omega$ - $3\omega$  scenario) or second harmonic waves ( $\omega$ - $2\omega$  scenario). For a bound-bound transition, no interference occurs with the  $\omega$ - $2\omega$  scenario because of the parity selection rule, while with the  $\omega$ - $3\omega$  scenario, an interference takes place and a transition strength can be manipulated by controlling the relative phase of two laser fields. For a bound-continuum transition, the phase-dependent interference can be observed even with the  $\omega$ - $2\omega$  scenario as long as the photoelectron or photodissociation signals are angle-resolved. Needless to say, the total ionization signal does not exhibit any phase-sensitive interference in such a case. As for the  $\omega$ - $3\omega$  scenario, the phase-dependent interference can be observed for both angle-resolved and angle-integrated ionization signals.

The potential use of the phase of lasers for the determination of the phase difference of continua has been briefly discussed so far, but a straightforward application of the  $\omega$ - $2\omega$  scenario instead of a single-color ionization does not improve the situation for that purpose: Under the presence of two laser fields, it is quite essential to know the precise values of laser intensities and the ratios of all transition amplitudes, if the standard method mentioned above is to be applied to extract the values of phase difference. The use of two laser fields simply introduces additional complexity, leading to the even lower reliability of the fitted quantities.

We investigate the possibility of the use of phase-controlled lasers for the direct determination of the phase difference of continua.

It turned out that the proposed method enables us to determine the phase difference between continua with different parities, for example,  $s$  and  $p$  continua, which cannot be measured otherwise. This would become possible by a careful choice of laser polarization and also by isolating particular partial waves of the continua of interest through angle-resolved photoelectron detection. In contrast to the conventional photoelectron angular distribution measurement, the phase difference is observed as a phase lag with this method with respect to the relative phase of two lasers. It is interesting to point out that, when this method is applied to light alkali-metal atoms such as Li, Na, or K, the ratio of the radial matrix elements does not play a role for the determination of phase difference. For heavier alkali-metal atoms such as Rb or Cs, the spin-orbit interaction plays an important role, and more careful consideration is necessary. Nevertheless, it is shown that the direct determination of the phase difference of continua is possible, in principle, even in such a case.

#### 5. Thick-liquid protection for inertial fusion energy

Stationary and oscillating jets under atmospheric and vacuum conditions are formed and studied in experiments for the use of thick-liquid blankets for protection of IFE target chambers, primarily focusing discussion on jet hydraulics for heavy-ion fusion chambers. The principle goal of thick liquid protection is to superpose a half meter or thicker layer of liquid between chamber structures and IFE targets, providing heat removal and shielding of structures, allowing high power density, stainless steel construction, and 30-year or greater lifetimes for chamber components.