

## Advanced Energy Transportation Research Section

K. Miyazaki, Professor  
T. Nakajima, Associate Professor  
K. Hata, Research Associate

### 1. Introduction

Our research interests are focused on the development and applications of advanced lasers which provide with new functions of coherent radiation, aiming at the goal of opening new fields of science and technology. The current research subjects are concerned with the development of high-intensity ultrashort-pulse lasers that are capable of producing strong optical fields in the fs ~ ps duration and their applications to the study of strong-field nonlinear interactions with atoms, molecules, and solid surfaces. Experimental study of coherent control of such strong-field interactions is also an important research subject to develop a compact, high-brightness coherent soft X-ray source and a new technology for laser material processing on atomic and molecular levels.

We have been developing 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 fs pulses. By frequency conversion of this laser output, we can use fs, high-intensity laser pulses in the blue and ultraviolet (UV) spectral regions. The high-intensity fs laser pulses are now used to study Coulomb explosion of simple molecules and the generation of high-order harmonics in gaseous media. On the other hand, based on optical parametric generation and amplification in nonlinear crystals, a broadly-tunable, high-intensity ps laser is under development.

This research section is also working on the theoretical study of nonlinear optics in the short-wavelength region and on the fundamental study of steady and unsteady heat and fluid flow in water, cryogenic liquids and liquid metals.

### 2. High-intensity, femtosecond Ti:sapphire laser

The high-intensity, fs Ti:sapphire laser developed allows us to approach new regions of physical

parameters, i.e., the ultrafast time and the extremely-high electromagnetic field. The CPA laser system, developed as one of our principal experimental facilities, 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 stretcher using a pair of grating, the first regenerative Ti:sapphire laser amplifier, the second and third power amplifiers, and a grating pulse compressor. The compressed pulse width is 40 fs with the pulse energy of 40 mJ, producing a peak power of 1 TW. The beam diameter is about 20 mm. It is observed that long distance propagation of this laser beam induces self-phase modulation as well as some pulse-width broadening. Also, we have improved the long-term stability of the laser output by new designs of optical components and the system configuration. The laser system can be operated for more than 10 hours without any severe change of the output characteristics.

Current technology for the high-intensity ultrashort pulse generation is mainly based on Ti:sapphire lasers, and then the output wavelength is limited to a spectral region of 800 nm. To produce high intensity ultrashort pulses in a shorter wavelength region, we have studied efficient second and third-harmonic generation of 1-TW laser pulses, and now the peak power of 0.1 TW in the blue (400 nm) region and 10 GW in the UV (266 nm) can be used for applications.

### 3. Broadly-tunable, high-intensity picosecond laser

For the experimental studies of resonance interactions of high-intensity ultrashort pulse lasers with matter, we are developing a broadly tunable, high-intensity ps pulse laser, using optical parametric generation (OPG) and amplification (OPA) in nonlinear crystals.

*Fig.1. Schematic diagram of the broadly tunable ps laser . (a) The pump laser system; (b) The OPG and OPA system.*

The OPG and OPA laser system are pumped by the third-harmonic (355 nm) pulses of a psec Nd:YAG laser amplification system. The pump laser configuration is shown in Fig.1(a). The seed ps pulses at 1064 nm in the pump laser system are generated by a cw mode-locked Nd:YVO4 laser using a semiconductor saturable absorber mirror. The mode-locked, 100-mW output is sent to a single -mode optical fiber transmission line, and a single ps pulse is injected into a flash-lamp pumped, Q-switched regenerative Nd:YAG amplifier. The amplified pulse is extracted from the regenerative amplifier and further amplified by a flash-lamp pumped Nd:YAG power amplifier. The output pulse energy at 1064 nm is about 70 mJ in 40 psec pulses. The pump laser operated at a repetition rate of 10 Hz is frequency tripled by KD\*P crystals. The third harmonic pulse energy is 9 mJ, and its pulse width is 22 ps.

Figure 1(b) show the optical arrangement of the OPG and OPA laser system using BBO crystals. The nonlinear crystals are cut at  $\theta = 29 - 30^\circ$  for Type-I phase matching. The 9-mJ UV pump pulse is partially reflected by a partial reflector, and the pulse energy of 2 mJ is used to pump the OPG. The pump beam diameter is reduced by a telescope consisting of a couple of positive and negative lenses down to  $\sim 2$  mm, and then the pump intensity is about  $3 \text{ GW/cm}^2$

*Fig.2. The OPA pulse energy as a function of wavelength.*

on the BBO surface. The BBO for the OPG is 15 mm in length and  $5 \times 4 \text{ mm}^2$  in cross section. Strong parametric fluorescence is generated from the BBO crystal by the single-pass pump. The transmitted UV pump pulse is separated from the generated fluorescence by a dichroic mirror and reflected back to the BBO crystal, while the parametric fluorescence is also reflected back to the BBO for amplification, after the temporal overlap between the pump and fluorescence pulses is adjusted by moving back and forth the total reflector for the fluorescence. The double-pass pump strongly amplifies the parametric fluorescence and produces intense laser pulses.

We observed the laser spectra with a spectroscopic measurement system consisting of an optical fiber, a spectrometer including three different gratings, a CCD detector, and a personal computer for controlling the system. The generated signal and idler pulses cover a broad spectral range of 400 - 2500 nm.

The generated pulses in the OPG stage are sent to the OPA through the dichroic mirror. The OPA apparatus consists of two identical BBO crystals of 8-mm long. These crystals are pumped by the residual 7-mJ UV pulses. The pump pulse is temporally adjusted by a delay line for the perfect overlapping with the seed pulse. The pump beam diameter is also reduced to about 2 mm by a telescope, and the maximum pump intensity is about  $10 \text{ GW/cm}^2$ . We measured the OPA output pulse energy as a function of the wavelength, and the results is shown in Fig.2. The maximum OPA pulse energy of 1.8 mJ is observed at 470 nm with the 1450-nm idler pulse energy of 0.3 mJ. The conversion efficiency from the pump to the output is 23 %.

We compared the OPG threshold and its wavelength dependence for BBO and LBO crystals. The results have shown that the threshold pulse energy

for BBO is much smaller than LBO over the whole spectral region concerned. Measurements were also made of the phase-matching for the tunable output, the wavelength dependence of the output spectral bandwidth, the group delay as a function of the OPG wavelength, the OPA gain at various pump intensities as a function of the output wavelength, the spatial intensity distribution of the OPA output, and the pulse width of the OPA pulses.

Further experimental study is in progress to improve the conversion efficiency of the OPG and OPA and to extend the tunable wavelength region down to 200 nm and to the vacuum UV.

#### 4. Strong-field ionization dynamics of molecules

We have started an experimental study of strong-field interaction with simple molecules, using the high-intensity fs Ti:sapphire laser pulses.

When diatomic molecules are subject to a strong linearly-polarized laser field, Multi-Electron Dissociative Ionization (MEDI) takes place, and the fragment ions having specific kinetic energies are predominantly ejected along the direction of laser polarization. It seems to be extensively accepted that this phenomenon is induced by the alignment of molecular axis along the incident laser field, especially for light molecules such as  $H_2$ ,  $N_2$ , and CO. This laser-induced molecular alignment may provide us with a new technique to control kinetic motion of molecules in gas phase and resulting optical properties of molecular gases. The detailed conditions to induce the molecular alignment, however, seem to be still unclear.

We did a preliminary experiment for the study of MEDI of diatomic molecules, using linearly and circularly-polarized, high-intensity fs laser pulses. Since the molecular alignment concerned can be induced only by the linearly-polarized light, the circular polarization may allow us to calibrate the molecular ionization process in the absence of alignment.

The experimental arrangement is shown in Fig.3. The peak laser power used is 1 TW at 800 nm, and the pulse width is 40 fs. The linearly-polarized output from the laser system is split into two beams. One of them passes through a  $\lambda/2$  plate that rotates the linearly-polarized E-field direction. The other travels through a  $\lambda/4$  plate to produce circular polarization. For the pump-probe experiments, the two beams are combined on axis with an adjustable time delay. The

Fig.3. Configuration for the double-pulse experiment.

laser beams are focused by a lens with a focal length of 15 - 30 cm into a vacuum chamber equipped with a time of flight (TOF) ion spectrometer. The focused laser intensity is in a range of  $(0.5 \sim 8) \times 10^{15} \text{ W/cm}^2$ . The  $N_2$  gas pressure is varied in the range of  $10^{-8} \sim 10^{-7}$  Torr, and the ions produced are detected by a microchannel plate detector in conjunction with a digital oscilloscope.

Figure 4 shows some examples of the typical TOF ion spectra observed with a linearly-polarized beam having its  $E$ -field (a) parallel and (b) perpendicular to the detection axis, (c) a circularly-polarized beam, and (d) double pulses consisting of the first one polarized perpendicular to the detection axis and the second 100-fs-delayed, circularly polarized one. As expected, the fragment ions produced by a linearly polarized beam show a strong anisotropy, depending on the polarization direction. Although the circularly-polarized light cannot produce any anisotropy, the spectrum (c) is very similar to (a), because only ions ejected to the direction parallel to the TOF axis are detected. Note that in the pump-probe experiment, the fragment ions coming from the (2,2) and (3,2) channels are greatly reduced by the first perpendicularly-polarized pulse.

In the pump-probe experiment, the fragment signals are observed to strongly depend on the first-pulse intensity, when a constant intensity is kept of the second circularly-polarized pulse. No significant decrease of any fragments is observed at the first-pulse intensity lower than about  $0.7 \times 10^{15} \text{ W/cm}^2$ . A monotonous decrease in the fragments is observed with increasing the first-pulse intensity. The signal reduction observed may suggest that the fragment alignment would be induced by the first pulse.

It has also been assumed that the anisotropy of

*Fig.4. Examples of the TOF ion spectra.*

ejected fragments can also be produced by an enhancement of the ionization rate that depends on the angle between the molecular axis and the laser electric field direction. To see the alignment dynamics with a different method, we compare the ion signals produced by the linearly and circularly polarized pulses having an equal field amplitude along the detection axis. The TOF apparatus used has a small acceptance angle for ejected ions, and then the fragment signals to be detected should be almost the same for two polarizations if no alignment is induced. An example of the results for  $N_2^+$  is shown in Fig.5. With an increase in the laser intensity, the fragments produced by the linearly polarized light increase faster than that induced by the circularly polarized.

The present experimental results suggest that the fragment alignment is certainly induced before explosion at the high intensity, and the degree of alignment strongly depends on the fragmentation channels or on the laser intensity. Further experiments are being performed to determine precisely what is the laser intensity level required to align a molecule, what pulse duration is necessary to align molecules, and how long does the alignment survives.

*Fig.5. Ion signals as a function of the laser intensity.*

## **5. Theoretical study of nonlinear optics in the short-wavelength region**

The use of the coherent property of radiation has led to several interesting findings in recent years, which are represented, e.g., by the subjects of lasing without inversion, electromagnetically induced transparency, enhanced linear and nonlinear indices of refraction. In these studies, laser-induced coherence between bound states plays an essential role to modify light-matter interactions.

We have analyzed the nonlinear response of an autoionizing medium. The scheme we have considered would be particularly useful to enhance nonlinearities in the short-wavelength region, since the transition wavelength between the ground and an autoionizing states usually lies in the UV-VUV region. We have found that the proper choice of the laser detunings could lead to the enhanced nonlinearities through two kinds of third-order processes associated with self- and cross-phase modulations, while cancelling the linear and the nonlinear absorptions. The proposed scheme would be particularly attractive in the VUV region, since neither of the two laser fields needs to be highly coherent, which, again, is due to the fact that the coherence in this system is established by strong non-radiative interactions.

## **6. Critical heat flux on vertical cylinders**

Critical heat fluxes on vertical cylinders of various inner diameters internally cooled by forced flow of pressurized water are studied for wide ranges of pressure, liquid subcooling and flow velocity. We are studying to clarify the effect of these parameters on the critical heat flux and to present the database to determine the most favorable conditions to realize the high flux heat removal from a diverter of a fusion test facility.