Dynamical active optics for hard X-ray lasers

Many functional laser devices have been developed for optical lasers. Better quality light is obtained with these devices, and now many applications use well controlled lasers. The history of optical laser science is a story of improving control of the light. The same approach is expected for hard X-ray lasers. After successful generation of X-ray lasers from a free electron laser facility [1,2], these expectations are increased. Today we see the production of well-tuned high-energy photons having high spatial coherence which can be focused to high intensity. These features will powerfully advance X-ray science. The results described here demonstrate a start of these developments for hard X-ray laser research.

In normal active optical devices, the propagation constants such as the optical refractive index are changed and/or modulated by light field itself or by applied electric or magnetic fields. The mechanisms include the Pockels effect, Kerr effect, self-phase modulation, self-focusing, and other nonlinear scattering. They change the light direction, temporal shape of the pulse, wavelength and so on. In the X-ray region, the fundamental optical constants (real and imaginary parts of the refractive index, $n-1$ and k) are much smaller than those at optical wavelengths. That means that the nonlinear coefficient is very small for hard X-rays so that higher intensity is needed to produce nonlinear effects. In this situation, we proposed to use the "*K*-edge absorption resonance" because that gives the largest change of optical parameters for hard X-rays. As shown in Fig. 1, the edge energy is shifted with ionization of a 1*s* electron. If the edge energy changes, we expect a large change in the optical constants.

The intensity required to produce and maintain a single vacancy in the *K*-shell in a solid is determined by the photo-absorption cross section and by the speed of refilling of the *K*-shell vacancy by *L*- and *M*-shell electrons. When we consider the photon energy of the present beamline in the SACLA facility, the candidate atoms are medium Z atoms from Ti (5 keV) to Zn (10 keV). The critical intensity for those atoms is several times 10^{19} W/cm^2. This X-ray intensity has been achieved for the first time in the newest two stage focusing system in the SACLA facility [3].

The first experiment for developing active optics in the hard X-ray range was performed at the EH5 station of the **BL3** beamline where a 50 nm focusing optics can be used [4]. We selected iron as a target material. The XFEL is tuned to the iron *K*-edge absorption (7.1 keV). The transmitted FEL X-rays are measured with a crystal spectrometer with 1D spatial resolution. Figure 2 shows intensity dependence of transmission of 7.13 keV X-ray. One order of magnitude increase of transmission is observed at I = 7 × 10^{19} W/cm^2. The change of the absorption starts at I = 10^{19} W/cm^2 and this number agrees with the predicted intensity based on a rate comparison between photo-ionization and Auger process. This result shows that we can change the imaginary part of the refractive index with an intense hard X-ray laser pulse. Due to the Kramers-Kronig relation, the real part of refractive index also changes in this high intensity interaction region. If we change the real part of refractive index with the intense X-ray laser, the spatial profile of the transmitted light should be changed. To see that, we examine the divergence profile of the transmitted pulse. In the

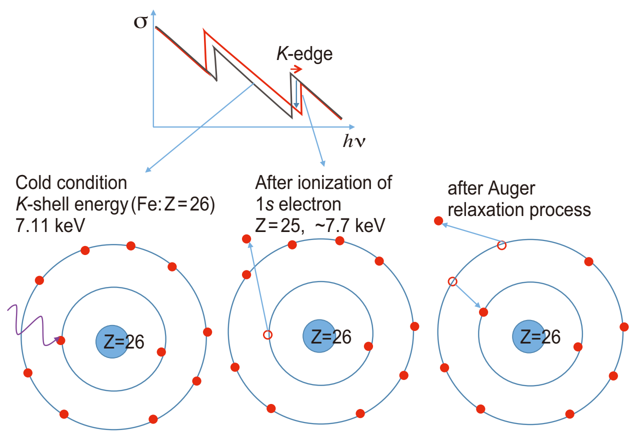

Fig. 1. The absorption edge spectrum changes with photoionization. After removal of one *K*-shell electron, the effective binding energy of the remaining 1*s* electron will increase by about 0.6 keV. This shift causes a relatively large transmission change.

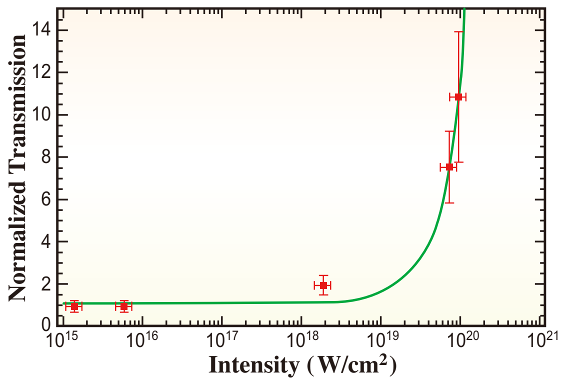

Fig. 2. Transmission normalized at the cold condition is plotted as a function of intensity at $h\nu$ = 7,130 eV for 20-μm-thick iron foil. The square dots show the experimental results, while the green lines are simulated curves with core-hole lifetimes of 2 fs.

experiment, we observe that the divergence angle of the transmission X-ray changes as shown in Fig. 3. At low intensity, the transmitted XFEL has 4 mrad expansion divergence, determined by the numerical aperture for the final focusing optics. At the highest intensity and for $h\nu > 7.13$ keV, this angle decreases to 2.3 mrad. That means dynamical spatial filtering occurs in the nonlinear optical interaction process. Similar mode cleaning is observed in saturable absorbers in the optical frequency region. To our knowledge, this is the first observation of this phenomenon in the hard X-ray region.

In conclusion, nonlinear transmission of X-rays is clearly observed in the multi-keV X-ray region for the first time. The threshold intensity for this nonlinear transmission agrees with the estimated value at which the rate of the photoionization equals the Auger rate. Intensity-dependent spatial filtering is also observed. These nonlinear transmission processes will be used for an ultra-fast X-ray switch in near future.

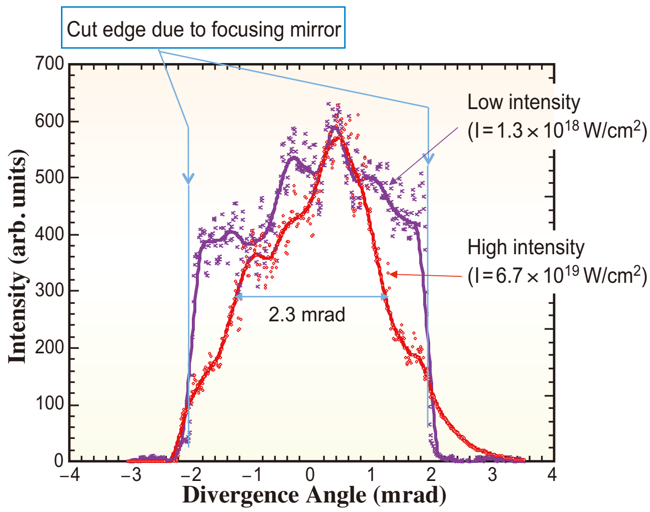

Fig. 3. Profile of angular divergence of the transmitted laser pulse. The red line shows high intensity results while the violet line shows a lower intensity case. The divergence of the beam incident on the target is limited by the acceptance angle of the final optics. The transmitted light has smaller divergence and a Gaussian-like profile.

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References

[1] P. Emma *et al.*: Nat. Photonics **4** (2010) 641.
[2]T. Ishikawa *et al.*: Nat. Photonics **6** (2012) 540.
[3] H. Mimura *et al.*: Nat. Commun. **5** (2014) 3539.
[4] *H. Yoneda, Y. Inubushi, M. Yabashi, T. Katayama, T. Ishikawa, H. Ohashi, H. Yumoto, K. Yamauchi, H. Mimura and H. Kitamura: Nat. Commun.* ***5*** *(2014) 5080.*