Development of an intense mid-infrared coherent light source for muonic hydrogen spectroscopy

S. Kanda,[*1] S. Aikawa,[*2] K. Ishida,[*1] M. Iwasaki,[*1] Y. Ma,[*1] Y. Matsuda,[*3] K. Midorikawa,[*4] Y. Oishi,[*5] S. Okada,[*6] N. Saito,[*4] M. Sato,[*5] A. Takamine,[*1] K. S. Tanaka,[*7] H. Ueno,[*1] S. Wada,[*4] and M. Yumoto[*4]

The proton is a fundamental constituent of the matter. However, its internal structure is complicated and perplexing. The internal structure of a proton is described by the electric and magnetic form factors. These form factors appear in the charge radius which has been measured by using electron-proton scattering and spectroscopy of hydrogen-like atoms. Since the proton charge radius was determined by the spectroscopy of Lamb shift in muonic hydrogen at PSI,[1)] there has been a significant discrepancy between the electronic and muonic measurement results of the charge radius.[2)] Both the experiments have been validated; however, the discrepancy was reproduced.[3,4)]

Alternatively, the proton structure is expressed by the Zemach radius, which is defined by a convolution of the charge distribution with the magnetic moment distribution. The Zemach radius can be extracted from the hyperfine splitting (HFS) of muonic hydrogen as a contribution arising from the finite volume effect of the proton. We aim to determine the proton Zemach radius via laser spectroscopy of the ground-state hyperfine splitting in muonic hydrogen. The HFS energy of muonic hydrogen is 183 meV, and it corresponds to a light having the wavelength of 6.8 μm. The hyperfine transition is E1-forbidden, and an intense mid-infrared coherent light source is essential to the experiment.

In order to perform precision spectroscopy of muonic hydrogen HFS, a pulse energy of 20 mJ and a spectral width of 100 MHz are required for the transition laser. The coherent light with a wavelength of 6.8 μm is generated by an optical parametric oscillator (OPO) using a $ZnGeP_2$ (ZGP) nonlinear optical crystal. The OPO is pumped with a Tm^{3+}, Ho^{3+} co-doped YAG ceramic laser. A quantum cascade laser (QCL) is adopted as a narrowband seeder. The output beam of the OPO is amplified by the ZGP optical parametric amplifiers (OPAs). Figure 1 illustrates a diagram of the proposed laser system.

As a first step to develop the laser system, the Tm,Ho:YAG ceramic laser was developed. A YAG ceramic rod was pumped by laser diodes and a quasi-continuous light output was pulsated by an acousto-optic Q-switch. A pulse energy of 20 mJ or higher and a pulse width of 150 ns or less are required for the output beam of Tm,Ho:YAG ceramic laser. Figure 2 shows the measured pulse energy and pulse width of the laser beam as a function of the current applied to the laser diodes. A TEM_{00} mode beam profile was obtained, and the beam radius was 1 mm. Sufficient performance of the light source was achieved by alignment optimization of each optical component.

Since the development of pumping light source was successful, the OPO pumped with the Tm,Ho:YAG ceramic laser will be demonstrated as the next step. The QCL as a seeder is under development and needs to be tested.

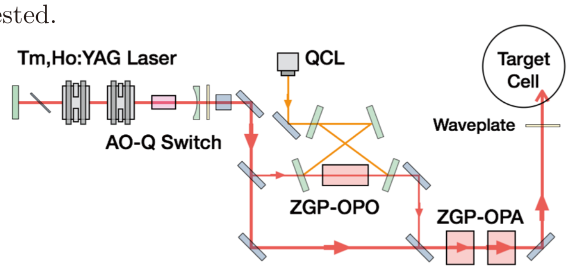

Fig. 1. Diagram of the laser system. The system comprises of three stages: the Tm,Ho:YAG ceramic laser; the QCL-seeded ZGP-OPO; and the ZGP-OPAs. A quarter-waveplate is placed after the OPA to obtain a circularly polarized light. In the spectroscopy experiment, two sets of the laser system will be employed for a total energy of 20 mJ.

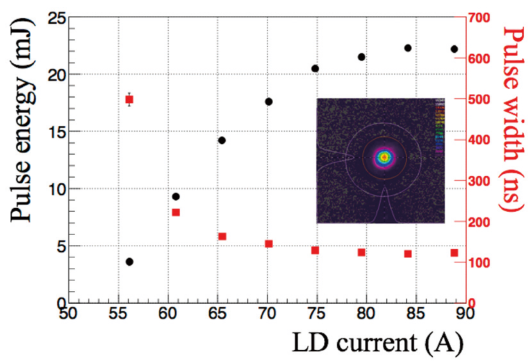

Fig. 2. Output characteristics of the Tm,Ho:YAG ceramic laser. The black circles correspond to the pulse energy, which refers to the left ordinate. The red squares correspond to the pulse width, which refers to the right ordinate. The inset represents the beam profile.

*1 RIKEN Nishina Center
*2 Department of Physics, Tokyo Institute of Technology
*3 Graduate School of Arts and Sciences, The University of Tokyo
*4 Photonics Control Technology Team, RIKEN
*5 High Energy Accelerator Research Organization (KEK)
*6 Atomic, Molecular, and Optical Physics Laboratory, RIKEN
*7 Cyclotron and Radioisotope Center, Tohoku University

References
1) R. Pohl *et al.*, Nature (London) **466**, 213 (2010).
2) P. J. Mohr, B. N. Taylor, D. B. Newell, Rev. Mod. Phys. **84**, 1527 (2012).
3) A. Antognini *et al.*, Science **339**, 417 (2013).
4) J. C. Bernauer *et al.*, Phys. Rev. C **90**, 015206 (2014).