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Development of mid-infrared laser for the measurement of muonic hydrogen atom hyperfine splitting energy

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Recently, the proton charge radius was measured using laser spectroscopy of the 2*s*-2*p* Lamb shift in muonic hydrogen (μp). Laser spectroscopy of μp resulted in 10 times higher precision of the proton charge radius determination than that of the ordinary measurements such as e-p scattering and hydrogen spectroscopy.[1)] As verification of the charge radius measurement, e-p scattering experiments were conducted at Mainz[2)] and the Jefferson Lab[3)], but the discrepancy in the results was not resolved. This raised a question as to whether the magnetic radius of the proton measured with muons will be consistent with that measured by electrons. Thus, we plan an independent measurement of the proton structure, i.e., the Zemach radius, to answer this question by using the hyperfine transition from singlet to triplet in the 1*s* state of muonic hydrogen atoms using the laser-spin-pumping method.[4)]

Two important requirements of the laser in this experiment are a high energy and narrow spectrum width. We need to generate pulse energy exceeding 40 mJ at 6.7 μm. In addition, a narrow spectrum width of 50 MHz is required. A mid-infrared laser system that produces pulse energy of 10 mJ at 6.1 μm has already been developed at RIKEN.[5)]

Based on this, we plan to construct a new laser system. The schematic of the laser is shown in Fig. 1. The laser system consists of a Cr:ZnSe master oscillator, Cr:ZnSe power amplifiers, and optical parameteric oscillators (OPOs) / amplifieers (OPAs). The Cr:ZnSe master oscillator and the power amplifier generate 100 mJ pulse energy per line at 2.4 μm. The pulse is introduced to the $ZnGeP_2$ nonlinear crystal (ZGP) OPO to achieve radiation at 6.7 μm. Two independent optical parametric oscillators and amplifiers will be prepared to achieve 40 mJ laser power in total and avoid damages to the ZGP crystal, which is difficult to synthesize with a large diameter. To realize a narrow band spectrum width of 50 MHz, we will introduce a single mode laser diode (LD) of 100 kHz as a seed laser. In this paper, we report the output characteristics of a Cr:ZnSe master oscillator (laser) and a single pass Cr:ZnSe power amplifier.

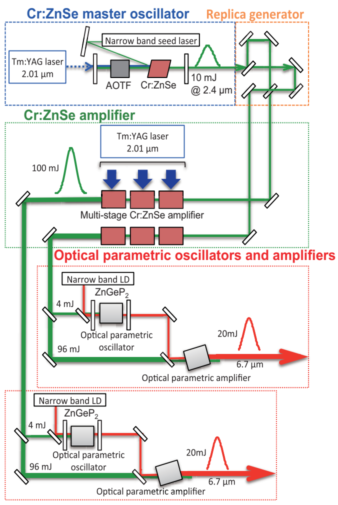

Fig. 1. Schematic of the laser

Figure 2 shows the output energy of the Cr:ZnSe laser. A maximum pulse energy of 5.8 mJ was obtained at 2.4 μm with a pump energy of 18 mJ. The conversion efficiency reached 32% at maximum. This value is excellent compared with those of other lasers for example, the $Ti:Al_2O_3$ laser and Nd:YAG laser.

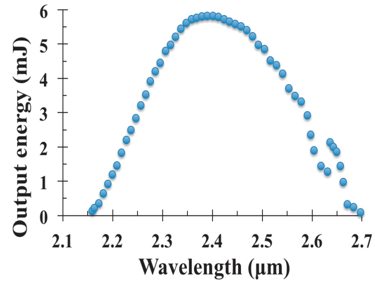

Fig. 2. Output energy of the for Cr:ZnSe laser

The output enegy extracted from the Cr:ZnSe power amplifier is shown in Fig. 3. The incident energy from the Cr:ZnSe laser was 5.5 mJ at 2.4 μm, and it was amplified to 26.3 mJ with increasing pump energy. A maximum conversion efficiency of 41.5 % was obtained with a pump energy of 50.2 mJ. This is, to the best of our knowledge, the highest conversion efficiency ever attained for a single-pass Cr:ZnSe power amplifier.

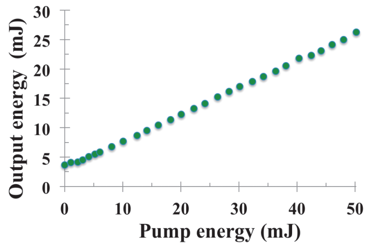

Fig. 3. Output energy extracted from the Cr:ZnSe power amplifier.

Based on the above results, to obtain an energy of 100 mJ at 2.4 μm, we need a pump energy of 240 mJ. However, if we introduce such an energy to the Cr:ZnSe, it will be damaged because the damage threshold on the surface of Cr:ZnSe is about 90 mJ. Therefore, we will construct three-stage Cr:ZnSe power amplifiers to solve this problem.

In the next stage, we will optimize the conversion efficiency of the Cr:ZnSe laser and the power amplifiers by controlling the crystal length and Cr^{2+} concentration. In addition, we will construct a three-stage Cr:ZnSe power amplifier and an OPO to generate radiation at 6.7 μm.

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