（別紙様式２）

フォトンサイエンス国際卓越大学院プログラム（XPS）

光科学特別実習　報告書

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Motivation of visit

I investigate the attosecond coherent control of atoms and molecules in RIKEN Center for Advanced Photonics. If we aim for higher fidelity of control or higher spectral precision by extending the delay time, cooling and trapping target atoms may be required. Those technologies are more and more applied in various fields including quantum computation [M. Saffman, T. G. Walker, and K. Mølmer, *Rev. Mod. Phys.* **82**, 2313 (2010)], quantum simulation [C. Gross and I. Bloch, *Science* **357**, 995 (2017); A. Browaeys and T. Lahaye, *Nat. Phys.* **16**, 132(2020)], and precision measurements [H. Katori, *Nat. Photon.* **5**, 203 (2011)].

I visited Prof. Ohmori's group in Department of Photo-Molecular Science, Institute for Molecular Science (IMS) in order to learn ultracold atomic physics with lasers. In addition, his group investigates the ultrafast measurements and coherent controls of cold atoms in optical tweezers and optical lattices. Therefore, I expected to exchange our ideas about the ultrafast laser technologies and to get a new view of my research.

Objective

Prof. Ohmori's group has been investigating the coherent dynamics of Rydberg atoms in optical tweezers and optical lattices in 0.1-1 ns timescale. Recently, the superradiance (or subradiance) dynamics of optically excited atomic clouds also attracts more interests in ultracold atomic physics. For example, the radiation dynamics induced by ultrashort excitation pulses of the order of 10 ns have been recently reported for a 650 μK ^{87}Rb cloud [G. Ferioli *et al.*, *Phys. Rev. Lett.* **127**, 243602 (2021)] and a Cs cloud coupled to a nanofiber [R. Pennetta *et al.*, *Phys. Rev. Lett.* **128**, 073601 (2022)]. However, only a limited number of reports have been made on the time-resolved measurements. Our knowledge of ultrafast and ultracold measurements would contribute to this field.

An interferometer with 10 ns range of the delay time requires an arm length of ~3 m, which is not easy to construct in a laboratory. An alternative way is the optical slicer, which produces the optical pulse from the continuous wave laser. In this method the delay time can be easily extended because the slice timing of slice is given by the electric signal. The recent development of the electro-optical modulator (EOM) enables the laser slicing shorter than 1 ns. Especially, the fiber EOM is now recognized to be very useful because the optical slicer can be compact and free from alignment.

Fig. 1 Photograph of the optical slicer. The optical pulses are sent to the chamber (back) through a fiber.

Contributions

I constructed the optical slicer (Fig. 1) based on the fiber EOM (NIR-MX800-LN-20, iXblue), and confirmed that optical pulses with a duration in the range of 300-1000 ps can be produced. Those sub-ns durations are convenient, because the typical Rabi period for the D2 transition of ^{87}Rb is 560 ps given the pulse with the power of 1 mW and the beam waist of 15 μm. However, I found that the limited extinction ratio of ~18 dB was very problematic. For example, the extinction ratio of 20 dB gives 100 times lower power of the pedestal with respect to the main pulse, and thus the pedestal of 5.6 ns already has the same pulse area with 560 ps pulse.

Therefore, I then tried to reduce the pedestal duration with a pre-slicing setup composed of two Pockels cells. Despite the shortest pulse duration given by each Pockels cell being longer than 100 ns, limited by the high voltage switch at hand (HTS 61-03-GSM, Behlke), we succeeded in generating a ~10 ns pulse by employing the two Pockels cells with delayed timings. The output pulse from the pre-slicer was further sliced by the fiber EOM.

The optical pulses were transported through a 10 m-long fiber and introduced into the experimental chamber. The easiness to transport the light to the different place is one of the good points of the fiber-based setup. The pulse was focused on the optical tweezer array trapping ^{87}Rb atoms [Y. Chew *et al.*, *arXiv* **2111**, 12314 (2021)]. The excitation from $5S_{1/2}$ to $5P_{1/2}$ is induced by the optical pulses, and the excitation probability is measured while varying the pulse duration of the fiber EOM trigger. A Rabi oscillation with a period of 5 ns was observed, indicating coherent excitation driven by the optical pulse. The oscillation period can be further shortened by introducing more power, but the coherence is so far limited by the scattering due to the ~10 ns pedestal. Therefore, further reduction of the pedestal would be the next step.

Experience through visit

I learned about laser cooling, quantum state manipulation and detection, which are quite different from the techniques in my research field. It was very fortunate because the coherent control of ultracold atoms becomes a more and more important technology in various fields including quantum computation, quantum simulation, and precision measurements. I also had many chances to discuss about the latest studies not only in Prof. Ohmori's group but also in the world, which broadened my horizons in the optical science.

The fusion between ultracold and ultrafast science is the very unique point of this group. At this point, I believe that I could also propose some ideas, not just learning. Although I had already been familiar with the attosecond and femtosecond techniques, I noticed that there are different importance and difficulties in the picosecond and nanosecond time regions. My knowledge of ultrafast science expanded a lot through this visit.