Performance characteristics of external cavities to generate
deep-ultraviolet coherent lights resonant to $3p^3P_1 - 4s^3P_0$
cyclic transition of $^{28}\text{Si}$

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Abstract

We developed a robust 252 nm single-mode coherent continuous-wave light source through two-stage highly efficient frequency conversion systems using external cavities. In the first stage, we obtained the second harmonics (SH) power of 630 mW from the LBO-installed external cavity by frequency doubling of a 746 nm Ti: sapphire laser with an efficiency of almost 50% [Y. Asakawa, H. Kumagai, K. Midorikawa, M. Obara, Opt. Commun. 217 (2003) 311.]. In the second stage, 252 nm light power was obtained by doubly resonant sum-frequency mixing of 373 nm light from the first-stage conversion system and 780 nm light from another Ti:sapphire laser. In the sum-frequency external cavity, the maximum 252 nm light power of over 150 mW is obtained, which is about three times larger than that obtained in our previous experiment.

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1. Introduction

The need of ultraviolet (UV) light for many applications has accelerated the development speed of the frequency conversion techniques and novel laser devices. One of the interesting application fields for UV laser is atom optics. Especially in relation to laser cooling of neutral atoms or ions, many research teams have worked to succeed in the laser-cooling experiments. In these circumstances, as we reported in previous paper [2], we have developed prototype-dedicated CW light source for laser cooling of $^{28}\text{Si}$ atoms. But this light source had lower power ($\approx 50$ mW) than we wanted and had low power stability and frequency stability. So, we had to improve these issues.

There are many experiments reported in regard to atom deposition, which is an application of laser cooling. Using a standing-wave laser, McClelland et al. demonstrated nanometer-order deposition of Cr atoms [3], and also McGowan et al. demonstrated both cooling and deposition of Al atoms [4]. Furthermore, Shimizu et al. demonstrated trapping of Neon atoms and then release these atoms toward a reflection-typed hologram to draw a micro-scale figure on the surface of a micro channel plate [5]. Though, nowadays, it is reported that various methods excluding laser sources to control the motion of atoms, laser itself still plays a main role in many applications around the research field of atom-optics. In this paper, we report the performance of a laser system that we arranged for laser cooling of $^{28}\text{Si}$ atoms.
2. Experiment

A schematic of the laser system is shown in Fig. 1. The external cavity is bow-tie shaped, consisting of two flat mirrors, two 50 mm concave mirrors and a non-linear crystal, so that the cavity resonate both 373 and 780 nm light. We re-constructed the cavity on the vibration-resistance board. One of the concave mirrors, M2, is mounted on a piezotransducer and the cavity length can be controlled with it so as to resonate the 373 nm light to the cavity. 373 nm light is the second harmonic light of Ti:sapphire laser (COHERENT MBR-110) and, it is delivered into the external cavity through M1, which is the input coupler for 373 nm light. Next, 780 nm light, which is the fundamental light derived from another Ti:sapphire laser, is delivered into the cavity through M4. The reflectance of both input couplers for the fundamental wavelength is 98% and that for the other is more than 99.8%. Output coupler M3 is trichromatically coated and its transmittance is 84.6% for generated 252 nm and reflectance is more than 99.8% for the two fundamental wavelengths. As for the reflectance of both input couplers, we discuss about optical impedance matching in the sum-frequency cavity later.

After the cavity length is locked with the piezotransducer, we tune the oscillation frequency of the incident 780 nm light exactly to the stabilized cavity frequency, so that both 373 nm light and 780 nm light resonate instantaneously in the same cavity. Therefore doubly resonant sum frequency generation is demonstrated. Additionally, we carefully optimized PI constants in the servo to be locked the cavity stable.

As a non-linear crystal, we employed 10 mm long type I, phase-matched $\beta$-BaB$_2$O$_4$ (BBO) crystal. Its cutting angle is 47.46°. The both incident beams are focused at the middle of the BBO crystal and the minimum diameter is about 25 $\mu$m at the middle of the crystal. Both facets of the BBO crystal are antireflection coated for two fundamental wavelengths, and the output end is also coated for high transmission for 252 nm light.

To avoid thermal effect in the BBO crystal, we placed a peltier device under the BBO crystal and electrically controlled temperature of the crystal precisely with the controller (OMRON E5EN). To stabilize the crystal’s temperature relatively higher than that of air, we made the temperature distribution uniform inside the crystal even when the enhanced laser light went through it.

3. Results and discussions

Fig. 2 shows the generated power and its conversion efficiency of 252 nm light extracted from the external cavity as a function of the incident 780 nm light power for each incident 373 nm light power. Considering the reflectivity of output coupler, the maximum generated 252 nm light power inside the cavity is estimated to be more than 150 mW. Three results with different incident 373 nm lights power are mapped on the graph. Though the maximum power is generated when 373 nm light power is 630 mW and 780 nm light power is 1200 mW, the maximum conversion efficiency is obtained under another condition, when the incident 780 nm light power and 373 nm light power are 920 and 630 mW, respectively, and its corresponding conversion efficiency is 8.5% as shown in Fig. 2. In regard of the output 252 nm light power, 150 mW is about three times larger than that of we obtained in our previous experiment [2]. And its conversion efficiency is also improved from 5 to 8.5%.
In the non-depleted approximation, the generated light power inside the cavity should be described as follows,

\[ P_{252} = \gamma_{SFG} \epsilon_{373} \epsilon_{780} P_{780} T_{OUT} \]  

where \( \gamma_{SFG} \), \( \epsilon_{373} \), \( \epsilon_{780} \), \( P_{780} \) and \( T_{OUT} \) are single-pass conversion efficiency, enhancement factor for 373 nm light, enhancement factor for 780 nm light, input 780 nm light power and transmittance of the output coupler, respectively.

But in practical, enhancement factor \( \epsilon \) is a function of intra-cavity total-losses and the reflectivity of input couplers. So, \( \epsilon \) is described by this equation for each incident light power,

\[ \epsilon_{373,780} = \frac{1 - R_{in,373,780}}{(1 - \sqrt{R_{in,373,780}(1-\alpha_{total,373,780})})^2} \]  

where \( R_{in} \), \( \alpha_{total} \) are the reflectivity of the input coupler, intra-cavity total-losses for the each incident fundamental light power, respectively. The intra-cavity total-losses consist of two kinds of losses, one is a passive loss \( \delta_1 \) and another is a non-linear depletion \( \delta_2 \) [6].

\[ \alpha_{total,373,780} = \delta_1 + \delta_2 = \delta_1 + \frac{\omega_{373,780}}{\omega_{373} + \omega_{780}} \gamma_{SFG} \epsilon_{373,780} \epsilon_{780,373} P_{780,373} \]

\[ \alpha_{total,373,780} = \delta_1 + \beta_{373,780} \gamma_{SFG} \epsilon_{373,780} \epsilon_{780,373} P_{780,373} \]  

Especially, \( \delta_2 \) includes photon-balance constant and this constant plays a very important role to represent the property of generated sum-frequency mixing power in such complicated three wave-mixing regime. Generally, the value \( \epsilon \) can be measured experimentally by detecting the ratio of the leakage lights from the output coupler with and without the cavity enhancement of the fundamental light [2]. If the intra-cavity losses \( \alpha_{total} \) were constant for all the region with input 780 nm power, \( \epsilon \) value would be also constant. So, three of the generated 252 nm power will have the constant inclinations and be proportion to the input 780 nm light power. But, as you can see in Fig. 2(a), they are not. As the input 780 nm light power increases, each of the generated 252 nm light power begins saturated in different input 780 nm light power. This is because \( \alpha_{total} \) increases as the input 780 nm light power increases. Fig. 2(b) shows the conversion efficiency of generating 252 nm light experimentally. In this figure, you can see that each of the graphs has a saturated point as the input 780 nm light power increases.

In general, sum-frequency mixing can be described with this equation,

\[ u_1 = u_2 + \beta \]

fig. 3. Enhancement factors of 780 nm light; (a) and of 373 nm light; (b) inside the sum-frequency cavity are obtained experimentally and shown as functions of each input light power.

fig. 4. The expected generated 252 nm light power; (a) and its conversion efficiency; (b) as functions of two input power are shown in the graphs. These graphs are obtained with intra-cavity passive losses; (\( \delta_1 \)) and single-pass conversion efficiency; (\( \gamma_{SFG} \)) and those are concurrently measured by experiment.
sum-frequency condition is roughly described below equation,

$$\frac{\varepsilon_{373} P_{373}}{\omega_{780}} = \frac{\varepsilon_{780} P_{780}}{\omega_{373}}$$

(4)

When we input 480 mW of 373 nm light power into the external cavity as shown in Fig. 3(a), the $\varepsilon_{373}$ is about 43. Therefore, utilizing Fig. 3(b) and Eq. (4), you can find out that $\varepsilon_{780}$ and $P_{780}$ are estimated to be about 80 and 530 mW, respectively, which is well-corresponded to the saturated point of generated 252 nm light power as shown in Fig. 2(b). By the same way, for input 562 mW of 373 nm light, 610 mW of 780 nm light power, and for input 630 mW of 373 nm light power, 660 mW of 780 nm light are estimated, respectively. Moreover, these estimated 780 nm light power is well-corresponded to each saturated point. Besides, each of saturated points is almost the highest in each regime. Therefore, using Eq. (4) enables us to predict efficient points in sum-frequency mixing. Here, we note that optical-impedance matching is not employed in this cavity, so the reflectivity of input-couplers (M1, M4) is not optimized in this regime.

The intra-cavity total-losses $\alpha_{\text{total}}$ can be detected experimentally by the reflected power from the input coupler and enhancement factor obtained above,

$$\alpha_{\text{total}} = \frac{P_{\text{in}} - P_{\text{r}}}{\varepsilon P_{\text{in}}}$$

(5)

By detecting leakage light from the cavity, passive losses of 373 nm light for each input power of 0.63, 0.56 and 0.48 W are found to be 0.9, 0.85 and 0.8%, respectively. And, passive losses of 780 nm light is 0.6% for any input power [7]. The single-pass conversion efficiency is $2.0 \times 10^{-4}$. Using these values above and Eqs. (1)–(3), easy calculations are employed so that we explore two input lights power dependence of the generated 252 nm light power and its conversion efficiency.

Results are shown in Fig. 4, which represents the expected generated 252 nm light power; (a) and its conversion efficiency; (b) as functions of two input light power. Fig. 4 expresses the tendency of the generated 252 nm light power and its conversion efficiency well. Comparing Fig. 2(a) and Fig. 4(a), you can find a similarity, the higher input 373 nm light power is, the larger the inclination of generated 252 nm light power is. And also you can see a good similarity between Fig. 2(b) and Fig. 4(b). As the input power of 373 nm light increases, the saturated point of conversion efficiency in each regime moves to the direction of higher input 780 nm light power. From these results, if we input more power of two lights into this cavity, we could obtain more 252 nm light power with high conversion efficiency. But it will be demonstrated with well-balanced two input lights power.

4. Summary

We demonstrated doubly resonant sum frequency generation to derive 252 nm coherent light form the robust external cavity using a BBO crystal. Over 150 mW of 252 nm light power was obtained by doubly resonant sum-frequency mixing of the 373 nm light and the 780 nm light. The conversion efficiency of about 8.5% is the highest value for the sum frequency generation adopting an external cavity to obtain around the light wavelength of 250 nm as our knowledge. Additionally, we proposed the idea to evaluate the characteristic performance of this cavity for getting higher conversion efficiency.

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