Sixth harmonic generation of 1064-nm laser in KBBF prism coupling devices under two kinds of gas conditions

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The conversion efficiency on the sixth harmonic of 1064 nm in $KBe_2BO_3F_2$ (KBBF) at different gas pressures in two kinds of gases, helium and nitrogen, is measured and compared. In the both gases, maximum conversion efficiency on the sixth harmonic of 1064 nm in high vacuum is nearly 10% of 355 nm, which is almost four times higher than that in low vacuum. The maximum average output power at 177.3 nm is 670 μW with the repetition rate of 10 Hz and the duration of 20 ps in high vacuum. It indicates that the sixth harmonic generation in high vacuum is more preferable than that in low vacuum.

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With the development of science and engineering, deep ultraviolet (DUV) lasers with high repetition rate and high beam quality were demanded in many fields[1]. Some methods such as the sum-frequency mixing (SFM) came into being and became one of the most fascinating subjects. The DUV coherent light from 172.7 to 187 nm, which was generated by SFM of the fourth harmonic of a Ti:sapphire laser and an idle infrared parametric pulse, was demonstrated in the LiB_3O_5[2]. A 157-nm coherent light source was developed as an inspection tool for F_2 laser lithography with four-wave mixing in Xe[2,3]. However, the nonlinear optical (NLO) crystal $KBe_2BO_3F_2$ (KBBF) gains an advantage over other NLO crystals for its easy-handling and enough birefringence for DUV harmonic generation with simple second harmonic generation (SHG)[4,5]. The sixth harmonic at 177.3 nm generated by KBBF in the nitrogenous conditions has been applied to the superconductors[6,7]. It indicates that the KBBF with prism coupling technique (PCT) will have a good vista in the future. Nearly all of the DUV experiments at 177.3 nm by SHG were performed at the normal pressure. The generation of DUV at 177.3 nm has not been studied in detail under different gas pressures and different gases, respectively. The DUV optimal experimental conditions under the vacuum environment were not known[8,9].

In this letter, we perform the experiments at 177.3 nm with the repetition rate of 10 Hz and the duration of 20 ps in helium and nitrogen under different gas pressures. When the nitrogen and helium pressure is nearly 0.005 MPa, the conversion efficiency is nearly 10% and it is nearly four times higher than that in the normal pressure. Our maximum output power of sixth harmonic is 670 μW, corresponding to one single pulse energy of 67 μJ. It means that the sixth harmonic generation in the high vacuum is more preferable.

The schematic of the experimental setup is shown in Fig. 1. For the plate-like nature of KBBF, it is very difficult to grow thicker. The phase-matching angle of 66.2° at 355 nm is too large to be processed by the KBBF crystal itself. So a special technique named PCT is adapted so as to make the light enter into the KBBF at the phase-matching angle. Figure 1(a) shows an optically contacted, prism coupled KBBF crystal. The reflection loss is neglected because the difference in refractive index between CaF_2 and KBBF is only 0.04 at 177.3 nm. In our experiments, the thickness of the KBBF crystal is nearly 1.4 mm. Before this KBBF prism coupling devices (PCD) was measured, it had been utilized as light source in an angle-resolved photoemission spectroscopy (ARPES) and the operation time was more than 500 hours[6]. It could be inferred that the conversion efficiency and output power of this degraded KBBF-PCD was lower than that of the new one.

As shown in Fig. 1(b), the laser at 355 nm with the repetition rate of 10 Hz and the duration of 20 ps is generated by the SFM of 532 nm and 1064 nm, which is very normal for the generation of 355 nm. The coherent light at 355 nm starts from a mirror with 355-nm high reflection at the angle of 45°. Following that, it transmits through an aperture with a diameter of 3 mm. And then the laser transmits through the lens system, the diameter of the laser becomes 1.5 mm, and it becomes a collimated light beam. At last it enters into the KBBF-PCD in a small chamber and transmits through a quartz glass at the Brewster angles.

The conversion efficiency on the sixth harmonic of 1064 nm at different gas pressures of the helium and nitrogen is shown in Figs. 2(a) and (b), respectively.

Except in vacuum environment, all the other experimental conditions are nearly the same.

From Fig. 2(a), it can be seen that the conversion efficiency at 177.3 nm increases from 2.18% to 9.40% with the helium pressure changing from the normal pressure to 0.005 MPa. The conversion efficiency in the high vacuum becomes nearly four times higher than that in the low vacuum. When the pump power increases up to ~5 mW, corresponding to the pump power density of ~1.2 GW/cm^2, the conversion turned into saturation. Almost all the previous sixth harmonic generation experiment at 177.3 nm was performed at the normal pressure, but it could be determined that a better results could be achieved in the high vacuum.

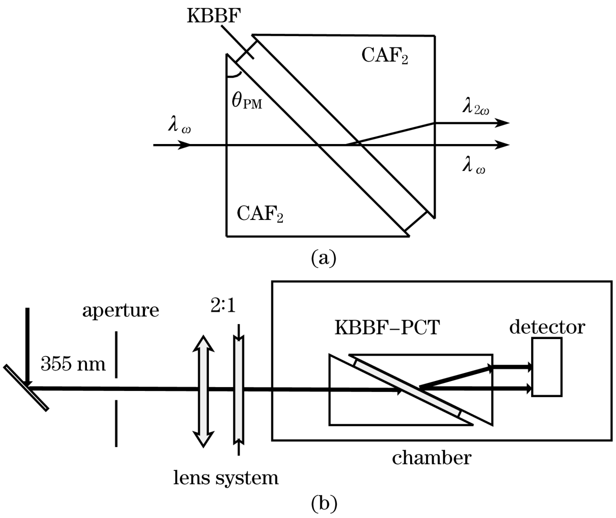

Fig. 1. (a) Schematic of KBBF-PCT and (b) experimental setup of the six harmonic of 1064 nm.

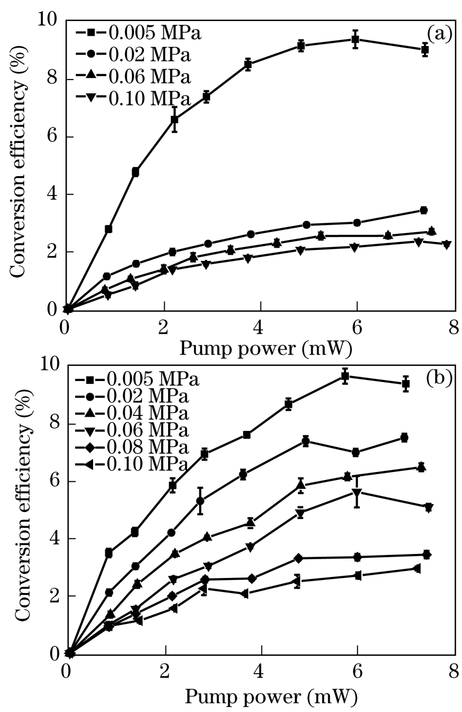

Fig. 2. Conversion efficiency of the six harmonic at 177.3 nm versus the input power at 355 nm at different pressures in (a) helium and (b) nitrogen.

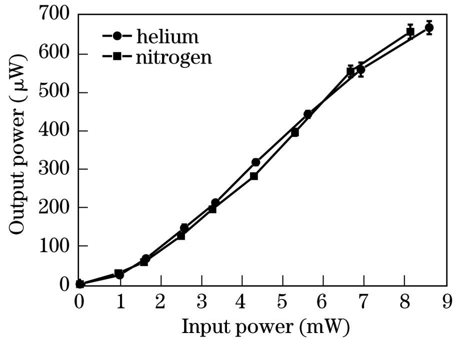

Fig. 3. Output power of the six harmonic (177.3 nm) versus the input power of 355 nm.

From Fig. 2(b), it is very easy to understand the conversion efficiency at 177.3 nm under the nitrogenous conditions. There is some difference in the conversion efficiency between the nitrogen and helium. When the nitrogen pressure changes from the normal pressure to 0.005 MPa, the conversion efficiency in nitrogen changes from 2.71% to 9.68% step by step and it becomes nearly four times higher, while in helium there is a very sharp change leap between the conversion efficiency at the pressure of 0.02 MPa and that at the pressure of 0.005 MPa.

In our previous experiments, the output power of 12.95 mW at 177.3 nm has been achieved, while it was performed at the normal pressure in the nitrogen[10]. If this experiment was performed in the high vacuum, the output power might be much higher than the original results. Figure 3 shows the relationship between the output power of 177.3 nm and the input power of 355 nm at 0.005 MPa in two kinds of gases. The maximum output powers in helium and nitrogen are 670 and 660 μW, respectively, corresponding to one single pulse power of 67 and 66 μJ.

According to the experiment, it could be determined that the conversion efficiency on the sixth harmonic generation of 1064 nm in the high vacuum was higher than that in the low vacuum. The highest conversion efficiency for the two different gases in the high vacuum was nearly the same. It indicated that the absorption for the gases molecular was very weak in the high vacuum and the high vacuum experimental condition was more preferable in the future work.

In conclusion, the sixth harmonic of 1064 nm (corresponding to 177.3 nm) in two kinds of gases, the helium and nitrogen, at different pressures was performed. When the nitrogen and helium pressures were about 0.005 MPa, the conversion efficiency was nearly ~10% and it was nearly four times higher than that at the normal pressure. Our maximum output power was 670 μW in the high vacuum helium and 660 μW in the high vacuum nitrogen. It gave us a good reference on the selection of the vacuum conditions.

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