国際会議 ISUPTW2016 において Best Conference Paper Award を受賞して

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The 8th International Symposium on Ultrafast Phenomena and Terahertz Waves (ISUPTW 2016) in Chongqing, China on Oct. 10th, which was an international symposium organized by Chinese Academy of Sciences (CAS) and the Optical Society of America (OSA) , evolved 150-300 participants every 2 years. On ISUPTW 2016 in Chongqing, there were more 200 participants and 8 persons won Best Conference Paper Award. The paper with the title of “High power Yb:YAG ceramics laser and diamond Raman laser for frequency conversion to DUV.” won the Best Conference Paper Award on this symposium. The content is about the high power Yb:YAG amplifier and new method by use of Raman laser to generate high power DUV laser at 193 nm that was carried out in Kobayashi Lab during last two years. The awarded contents will be introduced simply as following.

Extreme ultra-violet (EUV) laser lithography at 13.5 nm is now the most expected powerful technology to achieve the sub-10 nm node in the following years. However, it still takes a long time to overcome the power consumption and the throughput problems. ArF excimer laser at 193 nm with narrow-linewidth and high coherence is a profitable light source for interference lithography as a substitute towards the sub-10 nm node before EUV is ready[1]. Hence, the generation of deep ultraviolet (DUV) laser at 193 nm for seeding the hybrid ArF excimer laser is a necessary and important topic. Currently, the most popular method to generate ultraviolet (UV) or DUV laser is the frequency conversion scheme in nonlinear crystals such as second harmonics generation (SHG), sum frequency generation (SFG). In the past decades, it took a lot efforts for many studies to generate UV or DUV laser at 193 nm mainly focused on the Nd-doped lasers, Ti:Sapphire lasers or fiber lasers as fundamental. However, the reported fiber laser was running at CW mode or at lower power level, limiting the power scaling of DUV laser, as well as the Nd-doped lasers and Ti:Sapphire lasers. Thus, a high power fundamental power at longer wavelength is necessary for obtaining a high power UV and DUV laser.

Solid-state lasers such as the slab amplifier, the thin disk amplifier and the single crystal fiber (SCF) amplifier had demonstrated their ability of achieving hundreds of watts average output power. We have also already obtained 300 mW average power of DUV laser at 193 nm by use of a SCF amplifier as the fundamental [2]. This time we used a Yb:YAG ceramics rod amplifier (Φ=1mm, L=40mm) with a double-pass configuration[2]. The pump source was a 110 W laser diode (105μm, NA=0.22) at the wavelength of 940 nm. The seed laser for the Yb:YAG was at the repetition rate of 10 kHz with the pulse duration of 10 ns. The highest output of the Yb:YAG ceramics amplifier is 27 W at 1030 nm under the pump power of 116.3 W at 940 nm when the seed power of 1.25 W using a double pass amplification configuration as shown in Fig 1.

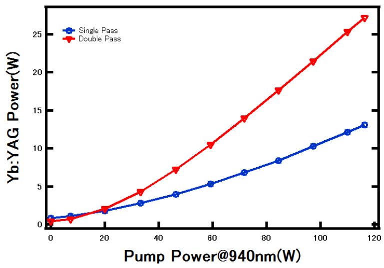

Fig.1 Yb:YAG SCF amplifier power pumped by a higher power LD at 940 nm.

We used the same LBO and CLBO crystal for SHG and FHG, respectively, as those in Ref. [2]. SHG and FHG powers were both demonstrated under the higher fundamental power of Yb:YAG ceramics laser. 15 W of 515 nm and 6 W of 258 nm were obtained, respectively. The conversion efficiency is more than 65% for the SHG and 40% for the FHG from 515 nm to 258 nm.

We used the above Yb:YAG ceramics laser and an external cavity figure to achieve the Raman laser oscillation. The experimental setup is demonstrated in Fig. 2. In the setup, the light at 1030 nm from the Yb:YAG amplifier was the pump. A convex focal lens (f=150 mm) was used to focus the pump beam to the surface of the diamond from the radius of ~700 μm. The Raman material is a CVD diamond with the dimension of 6×6×1.5mm^3 and anti-reflection (AR) coating at 1030 nm. The pump laser went through the diamond crystal direction of <110> which is the crystal axis. The laser cavity is a linear and short cavity with the length of 25 mm. The radius of the input mirror (M1) was 75 mm and the radius of the output coupler (OC) mirror was 50 mm. The coating for the input mirror was high transmission (HT) at 1030 nm and high transmission (HR) at both of the 1st and 2nd Stokes wavelength which is 1194 nm and 1420 nm. The OC mirror was coated with HR coating at 1030 nm and 1194 nm. Three different values of the output transmission at 1420 nm were tried experimentally which is 5%, 20%, and 50%.

light was 4.2 W. The slope efficiency with 50% OC was approximately 23%, which is a satisfactory value comparing to the previous reports.

This was a primary experiment for our next step of choosing suitable high power pump and high power Raman wavelengths to generate DUV laser at 193 nm. However, 1420 nm is still an interesting wavelength because its FHG is 355 nm, which is a common but useful UV wavelength in laser machining.

This time we reported a 27 W Yb:YAG ceramics rod type laser at 1030 nm . The SHG to green and FHG to UV laser power were 15 W and 6 W, respectively. A 6×6×1.5mm^3 CVD diamond was used as the Raman crystal in an external cavity pumped by this laser. The highest power of 0.586 W was obtained at the 2nd Stokes light at 1420 nm. To the best of our knowledge, it is the first time to achieve this wavelength by use of diamond Raman laser. Appropriate pump and Raman wavelengths will be studied in future for 193 nm laser generation.

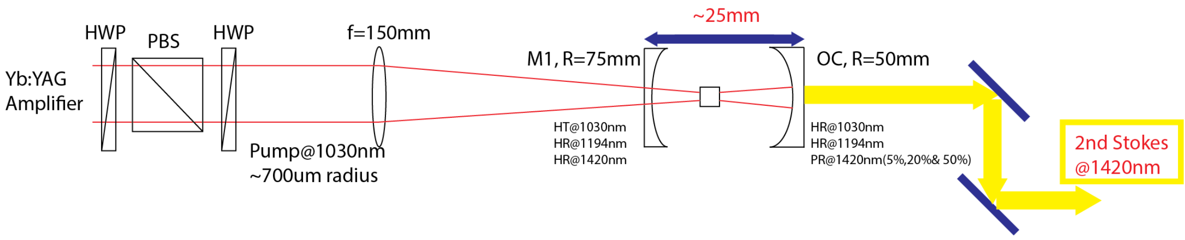

Fig.2 Setup of the external cavity diamond Raman laser (HWP: half wave plate)

After the Raman laser cavity, two reflection mirrors were used to remove the residual power of pump laser at 1030 nm and the tiny power of the 1st Stokes laser at 1194 nm for diagnostic of the generated 2nd Stokes laser. The Raman laser could easily achieve lasing at the pump laser power more than 1.25 W shown in Fig. 3. The threshold was difference for 3 OCs, which was around 1.5 W. It also depicted a higher OC corresponding to a higher threshold. To avoid the damage inside the cavity, the pump power for 5% and 20% OC was limited to 3.0 W. At the same pump of 3 W, the output power of the Raman laser at 1420 nm was 130.6 mW, 293 mW and 325 mW by use of 5%, 20% and 50% OC, respectively. The highest output power of 1420 nm was 0.586 W when the pump

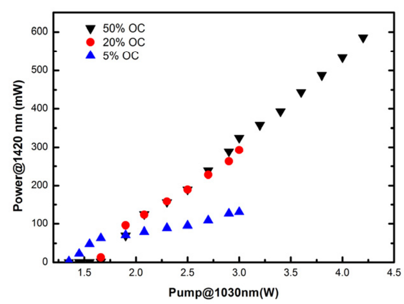

Fig. 3 Output Power of 2nd Stokes (1420nm) vs. Pump power

References

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