Balancing the conversion efficiency and beam quality of second harmonic generation of a two-picosecond Yb:YAG thin-disk laser

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Abstract

In this work, the optimization of the second harmonic generation in an LiB₃O₅ crystal of the 1 kHz, 2 ps Yb:YAG laser is being investigated. Depending on the crystal thickness, an optimal intensity exists, above which the back-conversion process negatively affects the beam quality and pulse shape, while decreasing conversion efficiency. For a selected 2 mm thick frequency doubling crystal, the conversion efficiency of 80% at an optimal intensity of 120 GW cm⁻² has been achieved, with output pulse duration of 1.3 ps and with beam quality of 1.4 and 1.6 in a horizontal and vertical direction, respectively, which is only slightly worse than the beam quality at a fundamental frequency.

Keywords: harmonic generation, ultrafast lasers, thin disk lasers, LiB₃O₅ (LBO), back-conversion

1. Introduction

Compact diode pumped thin-disk lasers can produce very stable near-infrared laser pulses of a duration in the order of few picoseconds and a high beam quality. They can also work at high repetition rates typically between 1–100 kHz, and with high average powers in the order of hundreds of watts [1]. They serve as essential tools in laser material processing, such as the fabrication of functional surfaces [2], and are also valued in the scientific community for e.g. laser-produced plasma extreme ultraviolet sources [3].

The second harmonic generation (SHG) of a high repetition rate, high average power picosecond lasers emitting at ≈1 μm wavelength is important to both the scientific community, because it allows one to pump optical parametric amplification (OPA) stages in large-scale laser facilities [4], as well as to industry for micromachining, such as welding and drilling [5, 6]. Finally, the green laser light can be converted further to the UV spectral region, which is useful for laser cutting and the manufacturing of electronic devices [7]. All of these applications need good conversion efficiency and an excellent beam quality.

There are several issues with the SHG of ps laser pulses, among which are e.g. group velocity mismatch, spatial walk-off, and back-conversion processes. These not only limit the energy conversion efficiency, but also distort the output pulse shape and beam profile, decreasing output beam quality. The highest obtained SHG conversion efficiencies are typically above 70% for 1 ps pulses [8, 9]. With 10 ps pulses, 80% conversion efficiency was achieved [10].
In this letter, we report on the optimization process of SHG of high repetition rate, high average power Yb:YAG thin disk laser. The optimization process is based on the evaluation of properties of the second harmonic (2H) beam generated in 2, 5, and 10 mm thick LiB₃O₅ (LBO) crystal. We show the detrimental effect of back-conversion on the beam quality. The shorter the crystal is, the higher beam quality can be achieved, with higher angular and spectral tolerances of the process. In the shortest crystal, maximum efficiency is also reached at higher input power, in comparison to longer crystals, resulting in greater available total output 2H power. However, high intensity of the input beam at fundamental frequency (1H) can cause third-order nonlinear effects, which, together with damage threshold of mirror and crystal coating layers, acts as the limiting factor. Therefore, the balancing of the parameters is needed.

2. Materials and methods

The schematic layout of the experiment is shown in figure 1. The 1H beam comes from an in-house developed chirped pulse amplifier based on the Yb:YAG thin-disk laser system, working on 1030 nm wavelength with a 1 kHz pulse repetition rate. The compressed pulse duration is between 1.8 ps and 1.9 ps and pulse energy is 6.5 mJ. The beam quality is high, with M² < 1.3 [11, 12].

The beam at fundamental frequency enters the Galilean telescope, which reduces the beam diameter. A half-wave plate and a thin film polarizer is then used to attenuate the power of the 1H beam to allow power dependency measurements. The power is measured by a reflection of an antireflection (AR) coated window and it is calibrated before each individual measurement. The 1H beam profile is measured after transmission through a high-reflection (HR) mirror, at the same distance, as is the input face of the crystal. After the frequency doubling in an antireflection coated LBO crystal, the 2H beam at a wavelength of 515 nm is isolated from the 1H beam by two dichroic mirrors. The 2H beam is then split by a wedged plate beamsplitter, one reflected part of the beam is used to measure the beam near field profile and the other part is used either for autocorrelation or for M² measurement. The transmitted beam is used for power measurements.

For the measurements, three LBO crystals were used. All were AR coated for wavelengths of 1030 and 515 nm at input and output faces. Phase-matching angles were θ = 90° and ϕ = 12.8° for 5 and 10 mm long crystals, and ϕ = 13.8° for the 2 mm long crystal. All crystals had the aperture of 8 × 8 mm².

Details about sensors used for measurements, as well as details about diameter, intensity and autocorrelation (AC) calculations are in the appendix. For our analysis, we can disregard effects of spatial walk-off, being only 8 μm mm⁻¹, as well as of temporal walk-off, which is 53 fs mm⁻¹.

3. Results

3.1. Conversion efficiency

First, all three LBO crystals were used and energy conversion efficiency (ECE) was measured, to find the crystal with highest attainable output 2H power and satisfactory beam profile. Results are shown in figure 2. For these results, the input 1H beam diameter was 3.67 mm. Insets show energy fluence profiles of output 2H beams at 515 nm, which is the frequency doubling wavelength.

Figure 1. The experimental scheme used for frequency doubling experiments. Legend: L—lens, HWP—half-wave plate, TFP—thin film Brewster-type polarizer, M—mirror, BD—beam dump, ARW—AR coated window, PM—power meter, LBO—nonlinear crystal, DM—dichroic mirror transmitting first harmonic and reflecting second harmonic, CCD—beam profile measurement, W—beam-splitting wedge, AC—autocorrelator, and M²—beam quality factor meter.

Figure 2. Measured dependency of frequency conversion efficiency and output 2H power on input fundamental beam peak intensity in LBO crystals of various lengths. The input beam diameter was 3.67 mm. Inset shows energy fluence profiles of output 2H beams.
3.2. Beam profile and M²

Spatial profile of the input 1H beam and the output 2H beam is shown in figure 4. Both beams are slightly elliptical and astigmatic. The 1H beam has a vertical and horizontal diameter of 0.48 mm and 0.52 mm, respectively, in position at the LBO crystal input face. The 2H beam has 2.0 mm in the vertical direction and 2.6 mm in horizontal direction 75 cm after the crystal. The beam is divergent and aberrated to a limited extent, which leads to phase-mismatch and, subsequently, a drop in a maximum achievable conversion efficiency.

As was already mentioned in the introduction, the back-conversion process started by small phase mismatch introduced by an aberrated beam can lead to decrease in 2H beam quality and ECE for higher than optimal input intensities. To evaluate this effect, we measured M² of the 2H beam in dependence on input 1H peak intensity. The results, together with beam profiles at various intensities and caustic measurement at optimal input intensity, can be seen in figure 5. First, the M² rises slowly from the 1.3 value at the fundamental frequency with increasing input intensity. At the optimal input intensity of 120 GW cm⁻², the beam quality is still very good, around 1.5. But as the intensity increases to more than 150 GW cm⁻², the beam quality factor rises sharply due to the onset of back-conversion.

3.3. Pulse duration and energy stability

The frequency up-converted pulses are usually somewhat shorter than the input pulses, because the low power edges of the 1H pulse are not converted efficiently. For the low...
efficiency regime, the 2H pulse shortening roughly follows $\tau_{2H} = \tau_{1H}/\sqrt{2}$, where $\tau_{1H} = 1.9$ ps is the duration of the 1H pulse. When the back-conversion is present, the 2H pulse can convert back to the 1H pulse, starting at the region of maximum intensity and thus distorting the pulse. To determine the pulse shortening effect, as well as the effect of back-conversion, the 2H pulse duration was measured (figure 6) through the means of autocorrelation. Below and at the optimal input beam intensity, the 2H pulse duration is about 1.3 ps, assuming sech^2 pulse shape, which results in a lower fit error than using the assumption of the Gaussian temporal pulse profile.

As one exceeds the optimal intensity, back-conversion begins to play an important role. The AC trace starts to differ significantly from the assumed pulse shape and it is not possible any more to make statements about the pulse duration from AC measurements alone. If phase mismatch and back-conversion are present, then as the input 1H intensity increases, the most intense part of the 2H pulse starts to convert back to the fundamental frequency. The pulse shapes are becoming more complex, the main peak is reduced and the expected pulse shape is similar to the super-Gaussian. The AC of the rectangular pulse is a triangle, and the measured AC trace, shown in figure 7(a), looks accordingly. As the input 1H intensity increases even further, the back-conversion eventually creates a double pulse. That is in agreement with the AC trace divided into three distinct peaks, shown in figure 7(b).

Finally, we measured the 2H pulse-to-pulse energy stability at different input intensities. The RMS was only about twice more than that of the 0.6% RMS of the driving laser, and was not much dependent on input intensities. At an input intensity of 50 GW cm$^{-2}$, the RMS of 2H energy in pulse per 100000 pulses was 1.2%. At the optimal intensity of 120 GW cm$^{-2}$, the RMS was 1.1% over 90000 pulses. At higher intensities, e.g. 190 GW cm$^{-2}$, the RMS was slightly lower, 1.0%. This reduced RMS of 2H pulse energy stability is caused by decreasing the slope of the 2H output average power dependency on 1H input average power, as can be seen in figure 3, green curve.

In contrast to our goal of reaching as high output power and beam quality as possible, back-conversion can be regarded as a simple picosecond pulse-shaping technique, which can be useful, e.g. for the pumping of OPCPA [13]. For this particular application, the flattop-like temporal profile of pump pulses (figure 7(a)), or even flattop pulses with pronounced edges (figure 7(b)), lead to enhanced total conversion efficiency of the OPA processes. More importantly, gain-narrowing is eliminated and the OPA bandwidth is much larger than without using non-trivial pulse shapes. As an added benefit, the pulse energy in the back-conversion regime is more stable.

### 4. Conclusions

To conclude, we have found the optimal parameters for second harmonic generation, which allow us to achieve high energy conversion efficiency of 80%, together with beam quality better than 1.6. To reach better output beam quality, one must sacrifice conversion efficiency and, eventually, available 2H output power. We identified the main problem, being phase mismatch and subsequent reconversion process, and we have shown the effect of this process on the pulse duration, beam quality and energy conversion efficiency.

The results are very valuable for the future upgrade of the driving laser to 100 mJ level at a 1 kHz repetition rate, which is planned for the near future. By increasing the crystal aperture and beam diameter, lowering the beam divergence will be possible. This will decrease the phase mismatch and suppress the back-conversion process, allowing us to achieve high ECE while maintaining excellent beam quality over a large variety of input powers.
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The authors declare no conflicts of interest.

Appendix

Input power of 1H beam was measured with an Ophir 3A power meter after reflection from an AR coated window. For the calibration of the power meter, the Ophir F150A-BB-26 power meter was used. For the measurement of the 2H output beam, a power meter of the same type was used. The available 2H power was measured without the beam-splitting wedge. A Spiricon SP620U was used as a beam profiler. The able 2H power was measured without the beam-splitting wedge. A Spiricon SP620U was used as a beam profiler. The beam diameter was calculated by BeamGage Standard 6.14 software as D4r with auto-aperture on. M2 was measured in accordance with ISO 11146 norm with a M2 meter supplied by Laser-Laboratorium Göttingen.

Autocorrelation traces were measured with an autocorrelator APE PulseCheck and fitted with function

\[ A_s(\tau) = \frac{3}{\sinh^2 \left( \frac{2.7196 \times (x+c)}{\tau} \right) - 1} \times \coth \left( \frac{2.7196 \times (x+c)}{\tau} \right) \times b, \]  

(A.1)

where \( \tau \) is delay, \( x \) is intensity of autocorrelation trace, \( a \), \( b \) and \( c \) are fit parameters and \( \Delta t = a/1.54 \) is real pulse duration (FWHM), if the pulse has a sech\(^2\) shape. With pulse duration \( \Delta t \), FW1/e\(^2\)M Gaussian beam diameter \( d \) and energy in pulse \( E \), peak intensity \( I_p \) was calculated according to the formula

\[ I_p = \frac{0.598 \times E}{(d/\text{mm})^2 \Delta t} \times 10^3 \, (\text{GW cm}^{-2}; \text{J, mm, ps}). \]  

(A.2)

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