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Comparison of intra-cavity THG between the single- and multi-pass operations

Shan Xu [a], Shufang Gao [a], Ge Zhang [b,*]

[a] School of Physics and Optoelectronic Engineering, Yangtze University, Jingzhou 434023, China
[b] Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou 350002, China

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ABSTRACT

Intra-cavity third harmonic generation was investigated comparatively in both single- and multi-pass operations from a side-pumped acousto-optic Q-switched Nd:YAG laser. Under the pump current of 19 A, 1.68 W and 2.2 W output power at 355 nm were obtained at 9.5 kHz in single and multi-pass THG operation respectively, with a power ratio of 76%. It clarified that the first THG process in multi-pass operation played a key role in the whole frequency-tripling process. The result provided the issue that efficient third harmonic laser could be achieved via optimizing the intra-cavity single-pass THG operation due to its high beam quality.

1. Introduction

In recent years, high-average-power all-solid-state ultraviolet (UV) lasers have been in great demand for many applications, such as micro-via drilling, biological investigations, medical equipment and wafer optical printing [1–3], because of the advantages of high reliability and low maintenance cost. Most devices applied in the mentioned applications are diode-pumped Q-switched Nd:YAG or Nd:YVO_4 lasers. However, research on 355 nm laser always focuses on extra-cavity third harmonic generation (THG) [4–7], in which the conversion efficiency is proportional to the power density. Therefore, in order to generate optimal conversion efficiency, increasing power density is always the first consideration, but this may easily cause damages to nonlinear crystal.

Just similar to intra-cavity second harmonic generation, intra-cavity sum frequency generation (SFG) is an efficient way to obtained 355 nm in solid-state laser. The conversion efficiency could be increased substantially because the power intensity of the intra-cavity fundamental laser is several orders of magnitude higher than that of extra-cavity. Besides, there are two main approaches for intra-cavity THG, single- and multi-pass operation [8–11]. If the third harmonic laser is produced by first mixing fundamental laser with the second harmonic laser, the SFG process is known as single-pass THG operation. However, there is a disadvantage during this operation, which is wastage of unconverted second harmonic laser because both the fundamental and second harmonic beam pass through the nonlinear crystals for SFG only once. Nevertheless, the intra-cavity multi-pass THG operation denotes that the generated second harmonic beam passes through the nonlinear crystals for SFG more than once. Therefore, much more second harmonic beams can meet the fundamental beam and convert to third harmonic. Generally, the output power will accumulate and be higher in this multi-pass THG operation.

In this letter, we investigated a comparative study of the THG performance in intra-cavity between single- and multi pass-operation. In multi-pass THG operation, the power of 355 nm generated when 532 nm beam passes through the second LBO first for SFG equals to the single-pass THG operation. This work clarifies that the power of first SFG generated in multi-pass operation plays a very key role in the overall THG performance. Due to high beam quality in single-pass operation, high power THG can be achieved via optimization of the intra-cavity single-pass THG operation.

2. Experimental setup

The experimental schematic of intra-cavity single-pass THG is shown in Fig. 1(a). A 3-mm diameter and 65-mm-long water-cooled Nd:YAG rod was side-pumped by diode arrays at 808 nm. M1 is a flat mirror with high reflectivity (HR, $R > 99.9\%$) at 1064 nm and high transmission (HT, $T > 99.9\%$) at 532 nm. M3 is HR at 1064 nm, 532 nm and 355 nm ($R > 99.7\%$). M2, a 45° folded mirror, is located between laser medium and LBO-SFG crystal. The face S1 of M2 is anti-reflective (AR) at both 1064 nm and 532 nm. Another face S2 of M2 is HR at 355 nm but HT at 1064 and 532 nm. To evaluate the differences of output characteristic

* Corresponding author.
E-mail address: zhg@fjirsm.ac.cn (G. Zhang).

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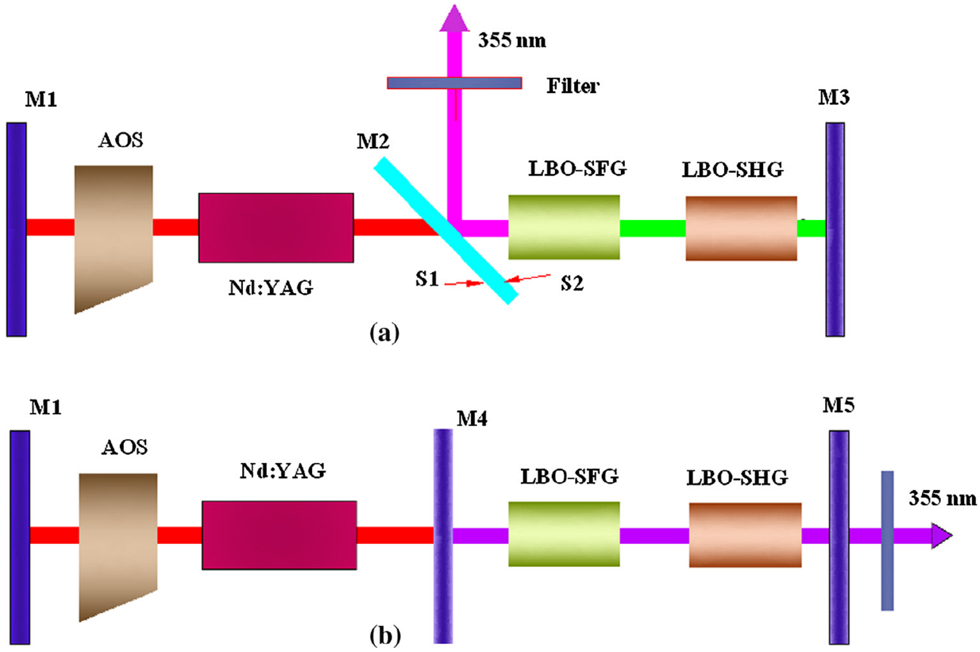

Fig. 1. Schemes of the intra-cavity single- (a) and multi- (b) pass operation.

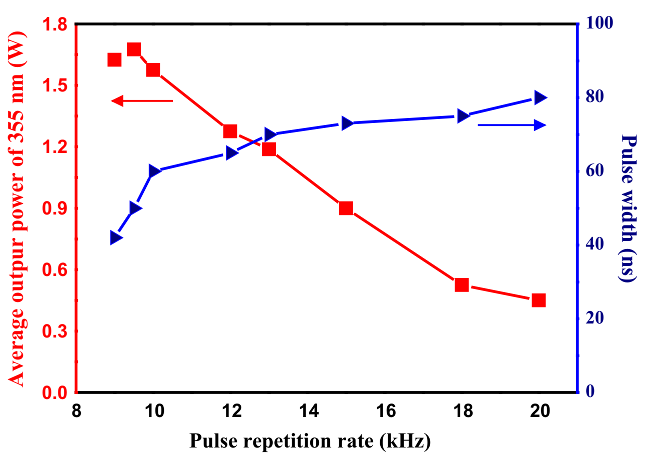

Fig. 2. Output power and pulse width in single pass THG operation versus with PRR.

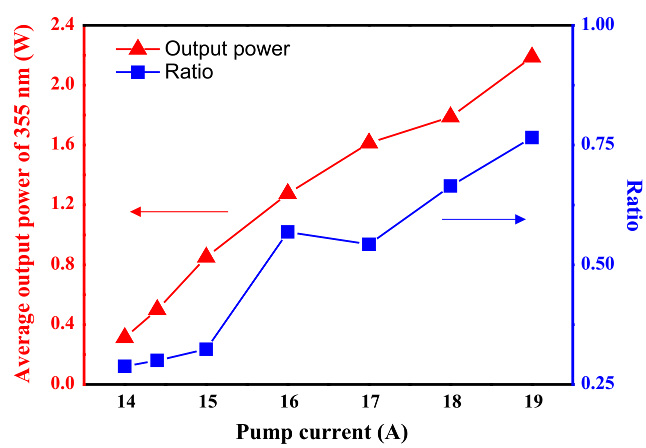

Fig. 4. Average output power and calculated ratio in the multi-pass operation.

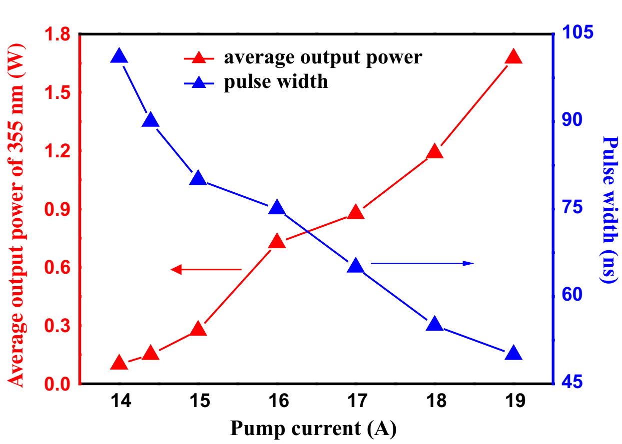

Fig. 3. Output power and pulse width of single-pass THG versus with the pump current.

between single- and multi-pass THG operations, we replaced the 45° folded M2 with M4 which is AR-coated at 1064 nm and HR-coated at both 355 nm and 532 nm. M3 is substituted by M5 which is HR-coated at 1064 nm and 532 nm ($R > 99.5\%$) and HT-coated at 355 nm ($T > 80\%$). The multi-pass THG schematic diagram is shown in Fig. 1(b).

Two LBOs (from CASTECH) are exploited as nonlinear crystals for both SFG and SHG because of prominent advantages. First LBO-SFG crystal, with the dimension of $4 \times 4 \times 15\ mm^3$, was cut at $\theta = 42.2°$, $\phi = 90°$ for type-II phase-matched. Second LBO-SHG crystal, cut for type-I critical phase-matched in the principal plane YZ ($\theta = 20.5°$, $\phi = 90°$), has a size of $4 \times 4 \times 10\ mm^3$. Both faces of LBO were AR-coated at 1064, 532 and 355 nm. They were wrapped with a thin indium foil and mounted in a copper holder, which was cooled and monitored by a thermoelectric controller at the temperature of 20 °C with the precision of 0.1 °C. In order to reduce the phase shift between the fundamental and second harmonic beam caused by air-dispersion, the distance between LBO-SHG and M3/M4 is infinitesimally small.