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80-W dual-wavelength green pulsed laser based on a Yb-doped rod-type fiber amplifier

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Abstract
We developed a high-power dual-wavelength green pulsed laser that generates 528-nm and 535-nm laser pulses which overlap completely in time and space. Two single-frequency seed lasers of 1056 nm and 1070 nm are combined and amplified to 140 W through a series of ytterbium-doped fiber amplifiers including a rod-type fiber amplifier, and the amplified laser pulses of two wavelengths are frequency-doubled, respectively, by two consecutive lithium triborate crystals. The total green power is more than 80 W at a 400-kHz repetition rate, and the power ratio between the two green wavelengths can be adjusted.

1 Introduction

Fiber lasers have advanced greatly over the last 2 decades in terms of laser power, efficiency, and robustness, and they are widely used in many industrial and scientific applications. Another capability of fiber lasers is that they can generate various lasing wavelengths. Depending on doping elements such as ytterbium (Yb), erbium, thulium, and holmium, a very broad range of laser wavelength can be covered by fiber lasers. Furthermore, most optical fibers doped by such rare-earth elements have broad emission spectra, which is very attractive for many spectroscopic applications.

For the study of resonant multi-photon ionization of specific atoms, multiple narrow-linewidth laser pulses of different wavelengths, which should overlap in time and space, need to be irradiated on target atoms [1]. Calcium isotopes, which are interesting elements for medical applications and the study of neutrinoless double beta decay [2], can be ionized by two green laser pulses of 528 nm and 535 nm with 272-nm laser pulses [3]. These two green laser pulses can be generated by the second harmonic generation (SHG) of Yb-doped fiber lasers. Since spatial and temporal overlap between laser pulses with different wavelengths is very important for efficient photo-ionization of atoms, careful spatial mode-matching between two laser beams needs to be achieved. When two laser beams are generated from separated laser sources, many free-space optics and careful alignment are required for spatial mode-matching, and thus, overall laser systems become complicated and unstable in long-term operation. Dual-wavelength fiber lasers offer a good solution for simple and robust spatial mode-matching because the beam modes of two lasers with different wavelengths generated from one common fiber laser are the same intrinsically.

For the effective and selective photo-ionization of specific calcium isotopes, on the other hand, the narrow linewidth and the high peak power of green laser pulses are also required, which is challenging for fiber lasers because a small core size and a long interaction length through optical fibers induces strong nonlinear effects. Recently, rod-type photonic crystal fibers (PCFs), which have a very large core size and a short length compared to conventional optical fibers, have been utilized for the generation of high-peak-power laser pulses [4–6], and high-power single-frequency laser pulses have been generated successfully from a rod-type PCF amplifier [7].

Dual-wavelength fiber lasers have been developed for many applications such as spectroscopy, distance measurement, and radio-frequency or THz generation [8–10]. However, their power levels have been only several watts or less, and the wavelength range has been limited in the near-infrared (NIR) range. Although dual-wavelength green lasers have been demonstrated based on solid-state laser materials such as Nd-doped lithium niobate, Nd:YVO$_4$ and Yb:YAG [11–13], the power level is still only several watts or lower, and the available wavelength range which can be covered by solid-state laser material is limited compared to fiber lasers.

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In this study, we developed a high-power dual-wavelength green pulsed laser based on Yb-doped fiber amplifiers, which can be used for the study of multi-photon ionization of calcium atoms. Seed pulses of 1056 nm and 1070 nm, which are generated synchronously from two separate seed lasers, are combined and injected into a series of fiber amplifiers, and the total amplified power of 140 W is obtained from a final rod-type fiber amplifier. After the SHG of 1056-nm and 1070-nm laser pulses with two lithium triborate (LBO) nonlinear crystals, a dual-wavelength green laser power of more than 80 W is generated. To our knowledge, this is the most powerful dual-wavelength green laser ever developed to date.

2 Dual-wavelength Yb-doped fiber laser

Since the wavelength and linewidth of laser pulses need to be controlled precisely for the study of photo-ionization of calcium atoms, we developed the laser system based on the configuration of a master-oscillator power amplifier, in which two narrow-linewidth seed lasers are amplified through Yb-doped fiber amplifiers. A rod-type PCF, which has been proven to be effective for high-power amplification of narrow-linewidth laser pulses [7], is utilized at a final power amplifier.

The laser system starts with two continuous-wave (CW) distributed-feed-back (DFB) laser diodes (LDs) with wavelengths of 1056 nm and 1070 nm, respectively, as shown in Fig. 1. The laser power and linewidth of the LDs are 20 mW and ~ 1 MHz. Two seed lasers are pre-amplified separately, and the configuration of the pre-amplification of each seed laser is the same. The CW seed laser is amplified to 200 mW by a Yb-doped polarization-maintaining (PM) single-mode (SM) double-clad amplifier, and the amplified CW laser is gated in the time domain by an acousto-optic modulator (AOM) and converted to a pulse train with a repetition rate of 400 kHz and a pulse duration of 13 ns. Since the power of the laser pulses is reduced to 0.3 mW after the AOM, it is amplified to 30 mW by the second pre-amplifier which has the same configuration as the first one. The amplified output from the second pre-amplifier passes through a fiber-coupled optical isolator in which a band-pass filter is installed for the block of a broad spectrum of amplified spontaneous emission. The output power is decreased to 15 mW after the isolator. The 1056-nm and 1070-nm laser pulses from the respective pre-amplifiers are synchronized for their temporal overlap by controlling the gating time of the AOMs.

After the pre-amplification of the 1056-nm and 1070-nm lasers, two laser beams are combined by a 50:50 PM SM directional coupler, yielding a power ratio of 1:1 between the two beams. The combined beam is coupled out to free space and injected into a Yb-doped flexible PCF with a mode-field diameter of 30 μm and a cladding size of 200 μm. The PCF is pumped by a 976-nm pump laser in the opposite direction of the signal injection, and the amplified power is 7 W, as shown in Fig. 2a. The power ratio of 1056–1070 nm (PR1056/1070), which can be measured easily by an optical spectrum analyzer, changes after the PCF amplifier because of the wavelength-dependent gain of the Yb-doped PCF. Since the gain at 1056 nm is higher than at 1070 nm in Yb-doped fibers, we observe that PR1056/1070 increases gradually to 1.5 as the amplified output power increases, as shown in Fig. 2a. The laser beam from the third amplifier passes through a free-space optical isolator and is injected into the final amplifier. Since the optical isolator is optimized at 1056 nm, the transmission of the 1070-nm beam is relatively lower, and PR1056/1070 increases to 2 after the isolator.

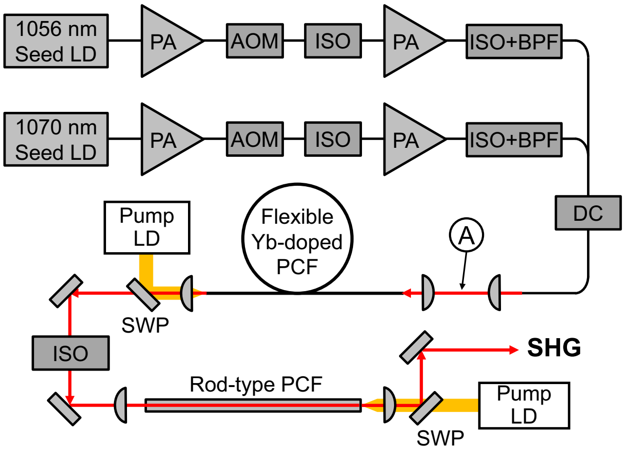

Fig. 1 Experimental setup of the dual-wavelength Yb-doped fiber laser system. *LD* laser diode, *PA* pre-amplifier, *AOM* acousto-optic modulator, *ISO* isolator, *DC* directional coupler, *BPF* band-pass filter, *SWP* short-wave passing dichroic mirror, *SHG* second harmonic generation. 'A' indicates the position where the laser power injected into the flexible Yb-doped PCF amplifier is measured

In the final power amplifier, we use a Yb-doped rod-type large-pitch PCF (LPF) which has a special hole structure with an optimized hole size and a hole-to-hole pitch for robust single-mode operation [14]. Such a unique hole structure enables highly preferential amplification of a fundamental mode and supports non-resonant wave-guiding over a broad wavelength range, which is important for good beam quality and wide wavelength tunability. The LPF used in the final amplifier has a mode-field diameter of 55 μm and an air-gap cladding diameter of 200 μm, and it is pumped by 976-nm pump LDs with a maximal power of 250 W. The small-signal pump absorption of the LPF is 24 dB/m at 976 nm, and the length of the LPF is 1.2 m.

Figure 2b shows the amplified output power from the final amplifier with respect to the pump power. The

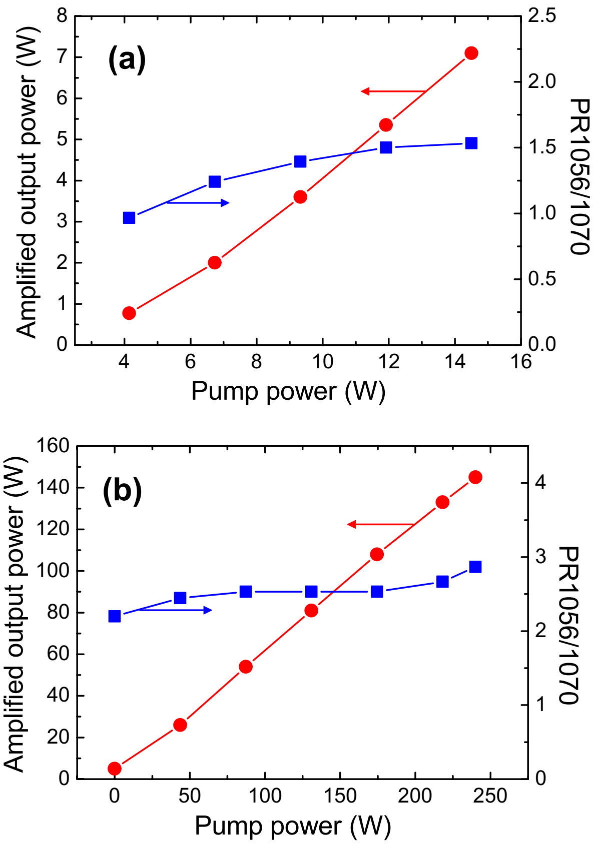

Fig. 2 Amplified output power and PR1056/1070 at **a** the third pre-amplifier and **b** the final amplifier with respect to the pump power

maximal output power is 145 W with an efficiency of 60%, and the amplified pulse duration is maintained at 13 ns at the maximal power. Because of the wavelength-dependent gain at the final amplifier, PR1056/1070 increases gradually from 2.2 to 2.9 as the amplified power increases. In the scheme of photo-ionization of calcium atoms, the power ratio between two green laser pulses is very important for the maximization of ionization efficiency; the laser power of 528 nm should be several times higher than that of 535 nm. Therefore, PR1056/1070 needs to be controlled before the SHG.

The power ratio is controlled by the adjustment of the power of 1070 nm at position A in Fig. 1 where the combined laser beam is coupled out to free space from the directional coupler. With the fixed 1056-nm power of 12 mW, the 1070-nm power at position A is varied from 3.9 to 12 mW, and PR1056/1070 is measured, as shown in Fig. 3. We found that the power ratio can be adjusted from 2.9 to 8 at the maximal amplified power of 140 W. The final amplified laser power is almost the same regardless of the variation of the 1070-nm laser power at position A, which indicates that the fiber amplifiers based on the flexible PCF and rod-type PCF operate at a highly gain-saturated regime. The M^2 value of the amplified output beam from the rod-type PCF was measured to be 1.1.

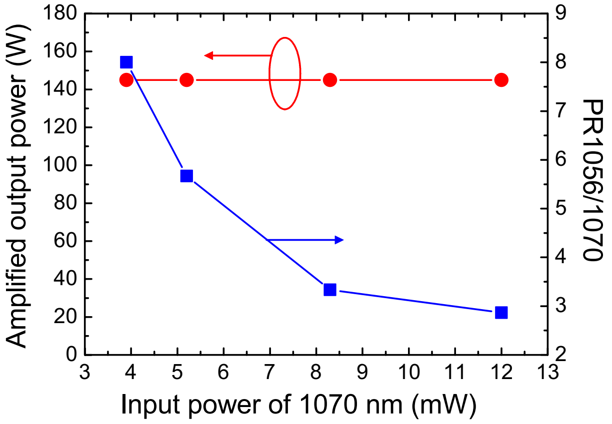

Fig. 3 Amplified output power and PR1056/1070 at the final amplifier with respect to the input power of 1070 nm at position A in Fig. 1. The power of 1056 nm at position A is fixed at 12 mW

3 SHG of dual-wavelength NIR laser pulses

For the generation of dual-wavelength green laser pulses, the dual-wavelength NIR laser pulses, which are generated from the laser system described in the previous section, need to be frequency-doubled by SHG. LBO crystals are very popular for the SHG of NIR lasers because of their high efficiency and robustness. LBO can be used in the configuration of non-critical phase matching (NCPM) for SHG of NIR laser pulses in the wavelength range of 1–1.5 μm, and very efficient SHG has been demonstrated with LBO crystals.

Figure 4 shows the experimental setup of the SHG of the 1056-nm and 1070-nm laser pulses in which two LBO crystals are used in series. The first LBO crystal is for the

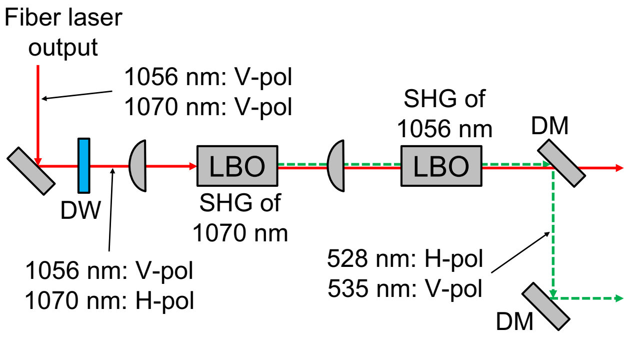

Fig. 4 Experimental setup of the SHG of 1056-nm and 1070-nm laser pulses. The polarization direction of laser beams is specified before and after SHG. *DW* dichroic waveplate, *LBO* lithium triborate crystal, *DM* dichroic mirror, *V-pol* vertical polarization, *H-pol* horizontal polarization

SHG of 1070 nm, and the second for 1056 nm. Both LBO crystals are fabricated in the configuration of type-I NCPM, and the temperatures of the crystals are tuned to 416 K and 431 K for 1070 nm and 1056 nm, respectively. The length of the crystals is 30 mm, and both ends of the crystals are coated for anti-reflection at 528–535 nm and 1056–1070 nm. The dual-wavelength laser beam from the final amplifier is focused to a 110-μm diameter ($1/e^2$) at the first LBO crystal, and it is refocused to a 160-μm diameter ($1/e^2$) at the second crystal; because the portion of the 1070-nm laser power is much lower than that of 1056 nm, the focused diameter of the 1070-nm laser beam is adjusted to be smaller for efficient SHG. After the LBO crystals for SHG, the green laser beam of 528 nm and 535 nm is separated by two reflections on dichroic mirrors which have high transmission at 1056–1070 nm (~95%) and high reflection at 528–535 nm (99.5%).

The 1056-nm and 1070-nm laser pulses from the fiber laser are polarized linearly in the same direction and overlapped completely in time and space. They also have a narrow linewidth of less than 100 MHz and a long coherence length of several meters. In such conditions, we found that the SHG efficiency at each LBO crystal was very low (less than 20%) even at the maximal laser power. Although the reason for such low SHG efficiency is not clear yet, we suspect that the interference between two narrow-linewidth laser pulses of different wavelengths ruins the phase matching for SHG at each wavelength. When the 1056-nm laser pulses were delayed and separated from the 1070-nm pulses in the time domain by controlling the gating time of the AOM, on the other hand, the SHG efficiency of 1056 nm was recovered to 60%, which suggests that the interference between 1056 and 1070-nm laser pulses degrades the SHG efficiency.

To achieve high SHG efficiency even when the 1056-nm and 1070-nm pulses overlap in time and space, we rotated the direction of linear polarization of the 1070-nm laser beam by 90° while leaving that of 1056 nm unchanged, and the first LBO crystal for 1070 nm was also rotated by 90° accordingly. For this, as shown in Fig. 4, we used a specially designed dichroic waveplate made of birefringent quartz; the thickness of the waveplate was carefully adjusted for half-wave retardation at 1070 nm and zero-wave retardation at 1056 nm. After the dichroic waveplate, the polarizations of 1056 nm and 1070 nm were perpendicular to each other, which insures no interference even with the temporal and spatial overlap of two laser pulses.

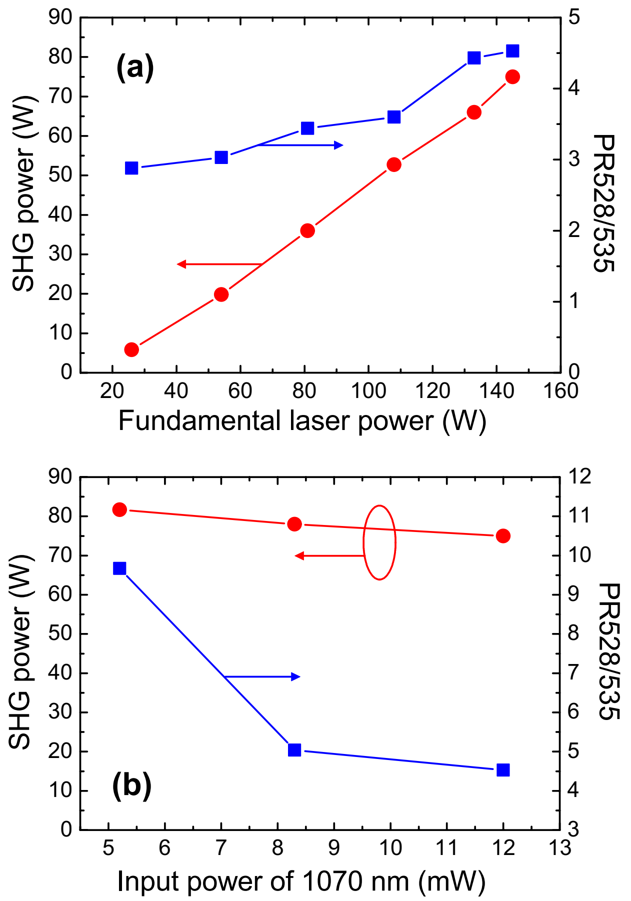

Fig. 5 **a** SHG power and PR528/535 with respect to the fundamental NIR dual-wavelength laser power. **b** SHG power and PR528/535 with respect to the input power of 1070 nm at position A in Fig. 1. The power of 1056 nm at position A is fixed at 12 mW

Figure 5a shows the power of dual-wavelength green laser and the power ratio of 528–535 nm (PR528/535) after the SHG, which was measured as the NIR laser power and PR1056/1070 was varied as shown in Fig. 3. The maximal green power is 75 W at the NIR laser power of 145 W, yielding a SHG efficiency of 52%. PR528/535 is 4.5 at the maximal power, which is higher than PR1056/1070 of 2.9. This indicates that the SHG efficiency of 1070 nm is lower than that of 1056 nm due to the lower power. The SHG efficiencies of 1056 nm and 1070 nm, which can be calculated from PR1056/1070 and PR528/535, are 57% and 36%, respectively, at the maximal power.

Since PR528/535 needs to be adjusted to ~ 10 for the optimal photo-ionization of calcium atoms, we measured SHG power and PR528/535 as PR1056/1070 was varied as described in previous section, and the results are shown in Fig. 5b. We found that PR528/535 of 9.7 was achieved when PR1056/1070 was 5.7 and that the total green power increased to 81.7 W. The SHG efficiencies of 1056 nm and 1070 nm, which were calculated from the power ratios before and after the SHG, were 60% and 35%, respectively. Figure 6 shows the spectrum of the dual-wavelength green laser with PR528/535 of 9.7, which was measured by a low-resolution spectrometer with a resolution of ~ 2 nm. The M^2 value of the combined green beam was measured to be 1.2.

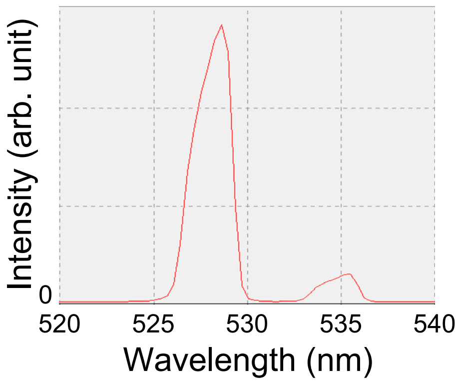

Fig. 6 The spectrum of the dual-wavelength green laser measured by a row-resolution spectrometer, which shows that the power ratio of 528–535 nm is 9.7

4 Conclusion

We developed a high-power dual-wavelength green laser system which can be used for the study of photo-ionization of calcium atoms. The dual-wavelength NIR laser pulses were generated by the amplification of seed laser pulses of 1056 nm and 1070 nm through Yb-doped fiber amplifiers. In the final fiber amplifier, an Yb-doped LPF was used for the generation of high-power laser pulses with a narrow linewidth. The maximal power of the dual-wavelength NIR laser was 140 W at 400 kHz, and the pulse duration was 13 ns. The 1056-nm and 1070-nm laser pulses were synchronized for the temporal overlap of dual-wavelength laser pulses, and PR1056/1070 was adjusted from 2.9 to 8. The dual-wavelength NIR laser pulses were frequency-doubled by the SHG based on two LBO crystals in series. For the efficient SHG of dual-wavelength laser pulses, which overlapped completely in time and space, the polarization of 1070 nm was adjusted vertical to that of 1056 nm by the use of a dichroic waveplate before SHG. The maximal power of the dual-wavelength green laser pulses was more than 80 W, and PR528/535 could be adjusted from 4.5 to 9.7.

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