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Electro-optically Q-switched dual-wavelength Nd:YLF laser emitting at 1047 nm and 1053 nm

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ABSTRACT

A flash-lamp pumped electro-optically Q-switched dual-wavelength Nd:YLF laser is demonstrated. Two Nd:YLF crystals placed in two cavities are employed to generate orthogonally polarized 1047 nm and 1053 nm radiations, respectively. The two cavities are jointed together by a polarizer and share the same electro-optical Q-switch. Two narrow-band pass filters are used to block unexpected oscillations at the hold-off state of the electro-optical Q-switch. In this case, electro-optical Q-switching is able to operate successfully. With pulse synchronization realized, the maximum output energy of 66.2 mJ and 83.9 mJ are obtained for 1047 nm and 1053 nm lasers, respectively. Correspondingly, the minimum pulse width is both 17 ns for 1047 nm and 1053 nm lasers. Sum frequency generation is realized. This demonstrates the potential of this laser in difference-frequency generations to obtain terahertz wave.

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1. Introduction

Solid state lasers emitting at two wavelengths are of significant interests due to potential applications in satellite laser ranging [1], holographic interferometry [2], determination of meteorological parameters [3] and nonlinear optical-frequency conversions [4]. Researchers have demonstrated synchronized dual-wavelength lasers utilizing different active media. Bethea [5] reported a dual-wavelength laser operating at 1064 nm and 1318 nm, utilizing an Nd:YAG crystal as the active medium. Shen et al. [6] investigated a large energy dual-wavelength Nd:YAP laser at 1079.5 nm and 1341.4 nm. Lunstedt et al. [7] researched continuous wave (CW) dual-wavelength operation of $Nd:GaVO_4$ laser at 912 nm and 1063 nm. Recently, dual-wavelength lasers with a small wavelength separation generated by stark split have attracted much attention [8–11]. In addition to the application fields mentioned above, they can also be used as pump sources for difference-frequency generation (DFG) to obtain longer-wavelength radiations, e.g. terahertz (THz) wave [12,13].

The Nd:YLF crystal is a promising dual-wavelength laser active medium because it can emit two radiations at 1047 nm (π polarization) and 1053 nm (σ polarization). And the two radiations have the stimulated emission cross sections of $1.8 \times 10^{-19}\,cm^{-2}$ and $1.2 \times 10^{-19}\,cm^{-2}$ at 1047 nm and 1053 nm, respectively. Zhao et al. [14] demonstrated a novel cavity using two crystals to generate two different output wavelengths. There are two advantages for this cavity. Firstly, the two lasers are generated from two crystals avoiding the gain competition of the two wavelengths in a crystal. Secondly, the two lasers are jointed together inside the cavity, so they can be good at spatial overlap. Zhao et al. [15] reported a passively Q-switched dual-wavelength Nd:YLF laser at 1047 nm and 1053 nm using a similar cavity.

In this paper, for the first time we demonstrated a flash-lamp pumped electro-optically (EO) Q-switched dual-wavelength Nd:YLF laser. Two Nd:YLF crystals emitting at 1047 nm and 1053 nm are respectively placed in two cavities. The two cavities share the same DKDP electro-optical Q-switch. The two radiations with the polarizations being orthogonal to each other were coupled by a polarizer and then output from an output coupler (OC). Compared with the conventional polarization beam combining technique, the intracavity beam-combining dual-wavelength laser system has some advantages, such as simple structure, good synchronicity and convenient control. The novelty of the cavity design lies in that two narrow-band pass filters are employed. With the filters inserted into the cavities, unexpected oscillations could be blocked and hold-off state of the electro-optical Q-switching process could be reached. In this case, electro-optical Q-switching is able to operate successfully. The highest output energy obtained was 66.2 mJ and 83.9 mJ for 1047 nm and 1053 nm lasers, respectively. Sum frequency generation (SFG) has been achieved to generate 525 nm visible laser line. This shows that the two pulses of 1047 nm and 1053 nm waves are well synchronized

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and spatially overlapped. The laser is suitable for future THz generation at 1.64 THz through DFG in a GaSe crystal.

2. Experimental setup

The experimental configuration is shown in Fig. 1. Two plano-concave mirrors (M1 and M2) were the rear mirrors with the same curvature radius of 3000 mm. They also had the same coatings for high reflection (HR) at the range of 1000–1100 nm ($R>99.8\%$). The output coupler (OC) was a variable reflectivity mirror ($2a=4$, $T_0=50\%$). It was selected to generate low divergence top-hat distributed beams. A polarizer (P) was placed inside the cavity at the Brewster angle. *C*-axis directions of the two *a*-cut Nd:YLF crystals were kept parallel to the *p*-polarization of the polarizer. So 1047 nm and 1053 nm lasers could oscillate in the cavities of M1-P-OC and M2-P-OC, respectively. Both lengths of the two cavities were 670 mm. The two Nd:YLF crystals were 1.0 at% Nd doped with a size of $\varnothing$5 mm × 80 mm. Each of them was respectively pumped by a flash lamp driven by a two-channel-output power source. The repetition rates were set to be 1 Hz. The two cavities shared a DKDP electro-optic *Q*-switch. We inserted a narrow-band pass filter (F1 and F2) into each arm of the laser. At normal incidence, their coating was for high transmission (HT) at 1064 nm ($T>97\%$) with a bandwidth of 5 nm. By adjusting the incident angle, the center of the pass band of F1 was tuned to be 1047 nm and that for F2 was tuned to be 1053 nm. If no filters inserted into the cavities, hold-off state of the electro-optical *Q*-switching process could not be reached. Take the 1047-laser as an example, after a round-trip through the electro-optical *Q*-switch with high voltage ($\lambda/4$) applied, the polarization state (*p*-polarized) of 1047 nm laser would change to be *s*-polarized. Then 1047 nm laser would be able to oscillate in M2-P-OC cavity. It was the same for 1053 nm laser. However, with filters inserted into the cavity, the unexpected oscillations were blocked and hold-off state of the electro-optical *Q*-switching process would be reached. In this case, electro-optical *Q*-switching is able to operate successfully. Then EO *Q*-switched dual-wavelength lasers could be realized.

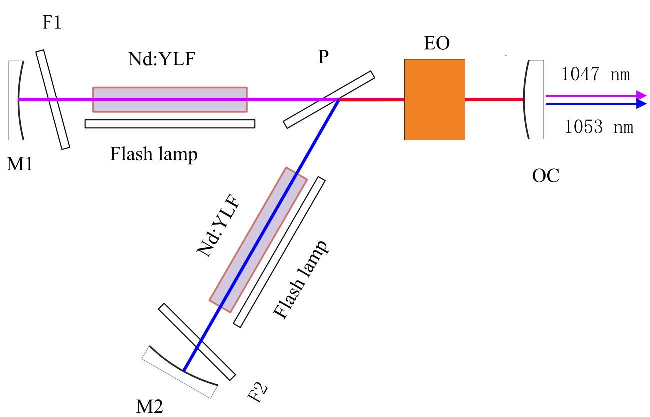

Fig. 1. Experimental setup of dual-wavelength Nd:YLF laser.

3. Results and discussions

Temporal overlapping of the dual-wavelength pulses could be controlled by adjusting the pumping energy of the lasers [14]. In our experiment, we adjusted the pumping voltage for 1047 nm laser while keeping that for 1053 nm laser at a certain value. Then the two laser pulses were synchronized. Under this condition, we obtained series of input and output data, as shown in Fig. 2. The output pulse energy was measured by a pyroelectric probe (Molectron J25LP) connected to an energy meter (Molectron EPM2000).

Laser radiation at 1047 nm was generated above the threshold of 650 V. The threshold of the 1053 nm laser was found to be 663 V. At

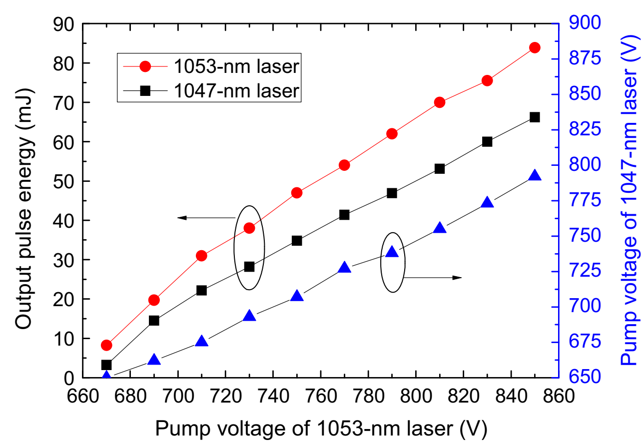

Fig. 2. Output pulse energy versus pump voltage at 1047 nm and 1053 nm.

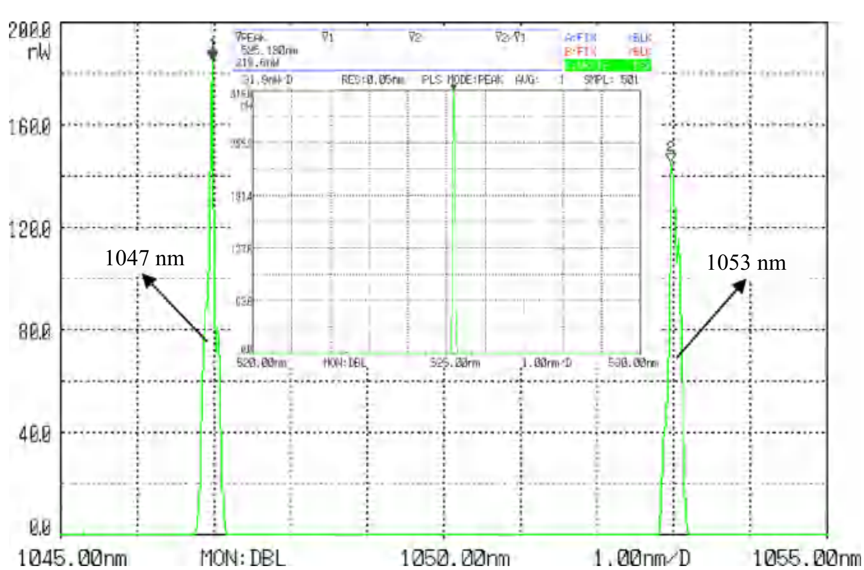

Fig. 3. Spectra of dual-wavelength laser at 1047 nm and 1053 nm. (Inset) The SFG spectrum.

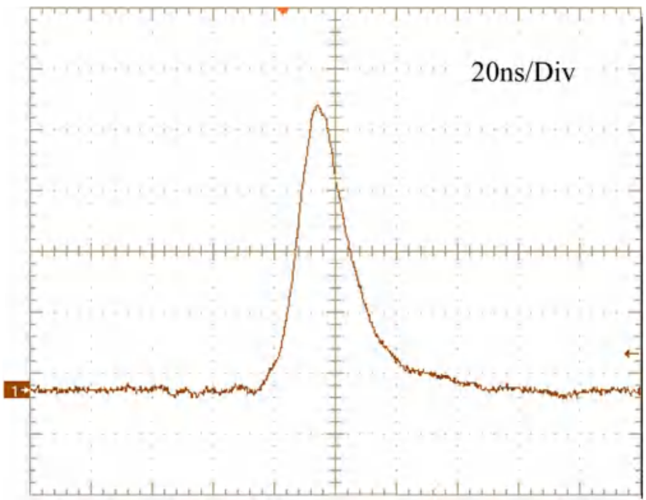

Fig. 4. Typical pulse shape with the two pulses synchronized.

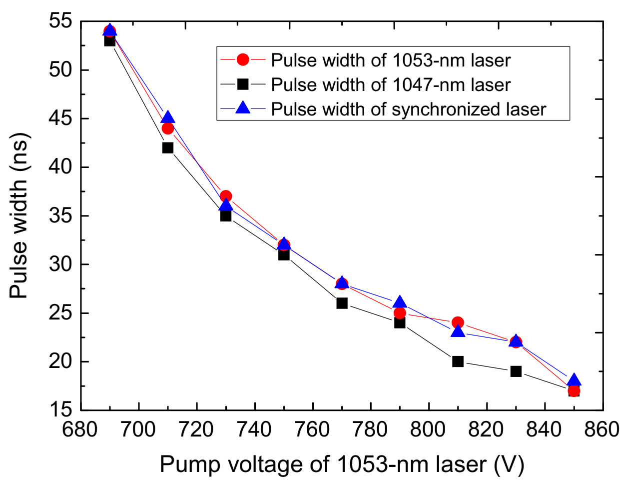

Fig. 5. Pulse width versus pump voltage.

the pump voltage of 792 V and 850 V, the maximum pulse energy was 66.2 mJ and 83.9 mJ for 1047 nm and 1053 nm lasers, respectively. Both of the 1047 nm and 1053 nm lasers have the diameter of 5 mm near the OC. The divergent angle was measured to be 0.3 mrad.

Fig. 3 shows the spectra of dual-wavelength laser emitting at 1047 nm and 1053 nm. It was recorded with an optical spectrum analyzer (Yokogawa AQ 6315A). The resolution was set to be 0.05 nm.

The pulse temporal behavior was recorded by a digital oscilloscope (Tektronix TDS5052B, 500 MHz bandwidth) with a fast photodiode. A typical oscilloscope trace is shown in Fig. 4. It was recorded with the highest output energy. The Nd^{3+} ions emission is very sensitive to the phonon subsystem and to the slight matrix disorder [16]. So, it is beneficial to realize the synchronization of the two pulses if the two active media with similar stimulated emission cross sections. The Nd:YLF crystal has the stimulated emission cross sections of 1.8×10^{-19} cm^{-2} and 1.2×10^{-19} cm^{-2} at 1047 nm and 1053 nm, respectively. It is feasible for us to choose two Nd:YLF crystals as the laser active media. In addition, once the laser active media and the cavity are designed, the synchronization of the two pulses from two cavities could be changed by adjusting the pump energy of the two cavities [14]. In our experiments, we adjusted the pumping voltage by monitoring the time overlapping state of the two pulses. If two peaks were observed, they were not synchronized. If only one peak was observed, we considered that these two laser lines were synchronized. As shown in Fig. 4, we could say that the two pulses were synchronized.

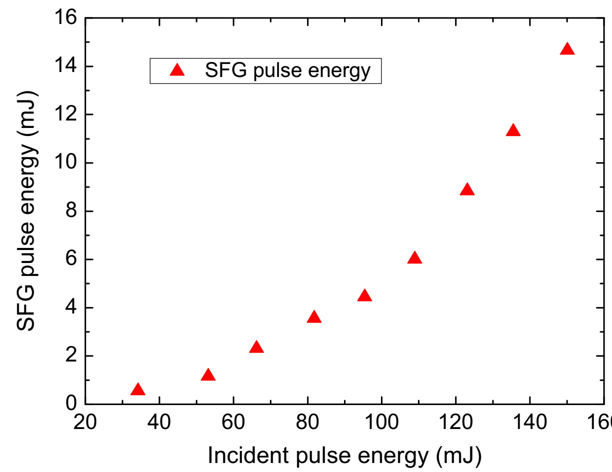

Fig. 6. The SFG pulse energy with different incident pulse energy.

Fig. 5 shows the variations of the pulse widths versus the pump voltage. As mentioned above, the pulse width of the synchronized laser was obtained when the two laser beams were incident to the photodiode simultaneously. The pulse widths of 1047 nm laser or 1053 nm laser were measured with the other laser beam blocked. It was found that with the pump voltage increasing, the pulse width decreased from 53 ns to 17 ns for the laser of 1047 nm and from 54 ns to 17 ns for the laser of 1053 nm, respectively. The pulse width of synchronized laser also decreased from 54 ns to 18 ns. At each pump voltage, the pulse widths of 1047 nm laser, 1053 nm laser and the synchronized laser were quite close to each other. It indicated that our judging criterion for synchronization was reasonable. If there was a considerable difference between the pulse widths for 1047 nm and 1053 nm lasers, this criterion would not be suitable. At the maximum output pulse energy, we got the pulse width of 17 ns both for 1047 nm and 1053 nm lasers, corresponding to a peak power of 3.89 MW and 4.94 MW, respectively.

Then we demonstrated sum-frequency generation (SFG) using the dual-wavelength laser. Extracavity SFG is also an effective method of testing the synchronization of the two pulses. The SFG medium was a KTP crystal with dimensions of $7\times7\times7$ mm^3. The relationship between the output energy of the SFG pulse and the total incident pump energy of the two laser beams is shown in Fig. 6. At the total incident pulse energy of 150.1 mJ (66.2 mJ of 1047 nm and 83.9 mJ of 1053 nm), the highest output SFG energy was 14.66 mJ, corresponding to an optical-to-optical conversion efficiency of 9.8%. We measured the spectrum of SFG by using the optical spectrum analyzer. As shown in the inset of Fig. 3, only peak at 525.18 nm was observed. The spectrum analyzer has an error of about 0.2 nm at the wavelength of 525 nm. There were no second-harmonic generated (SHG) peaks of 1047 nm and 1053 nm lasers.

4. Conclusions

We investigated the flash-lamp pumped EO *Q*-switched dual-wavelength Nd:YLF crystals laser emitting synchronized pulses at 1047 nm and 1053 nm. The two cavities were jointed together by a polarizer to generate perpendicularly polarized beams. By employing two narrow-band pass filters, electro-optical *Q*-switching was able to operate successfully. In the case of pulse synchronized, the maximum output pulse energy of 66.2 mJ and 83.9 mJ was obtained for the laser of 1047 nm and 1053 nm, respectively.

Different wavelengths can be generated by replacing the two Nd:YLF crystals by other laser active media. For example, we can generate dual-wavelength radiations at 1053 nm and 1079 nm after replacing a Nd:YLF crystal by a Nd:YAP crystal. Radiation of 525 nm was achieved using KTP as the SFG medium, which indicated the synchronization of the two pulses was realized.

Acknowledgments

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