Tunable GHz pulse repetition rate operation in high-power TEM_{00}-mode Nd:YLF lasers at 1047 nm and 1053 nm with self mode locking

Y. J. Huang, Y. S. Tzeng, C. Y. Tang, Y. P. Huang, and Y. F. Chen*

Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan
*yfchen@cc.nctu.edu.tw

Abstract: We report on a high-power diode-pumped self-mode-locked Nd:YLF laser with the pulse repetition rate up to several GHz. A novel tactic is developed to efficiently select the output polarization state for achieving the stable TEM_{00}-mode self-mode-locked operations at 1053 nm and 1047 nm, respectively. At an incident pump power of 6.93 W and a pulse repetition rate of 2.717 GHz, output powers as high as 2.15 W and 1.35 W are generated for the σ- and π-polarization, respectively. We experimentally find that decreasing the separation between the gain medium and the input mirror not only brings in the pulse shortening thanks to the enhanced effect of the spatial hole burning, but also effectively introduces the effect of the spectral filtering to lead the Nd:YLF laser to be in a second harmonic mode-locked status. Consequently, pulse durations as short as 8 ps and 8.5 ps are obtained at 1053 nm and 1047 nm with a pulse repetition rate of 5.434 GHz.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3530) Lasers, neodymium; (140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers.

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1. Introduction

High-power mode-locked solid-state lasers with multi-GHz pulse repetition rate are attractive in a great number of applications including high-speed optical sampling, optical clocking, ultrafast spectroscopy, high-capacity telecommunication, and so on [1]. The Nd:YLF crystal is specifically characterized by the negative dependence of the refractive index on the temperature, which can partly compensate for the positive contribution from the end-face bulging of the gain medium to exhibit a relatively weak thermal-lensing effect. As a consequence, the Nd:YLF crystal is recognized as one of the most competitive candidates for constructing high-power lasers with excellent output beam quality. In addition, the natural birefringence enables the Nd:YLF crystal to easily emit a linearly polarized beam and completely eliminate the possibility of the thermal depolarization under the high-power operation. More importantly, the Nd:YLF crystal has a gain bandwidth wider than 1 nm at the transition line of $^4F_{3/2} \rightarrow {}^4I_{11/2}$, which is more favorable for generating short-duration mode-locked pulses as compared with other Nd-doped laser crystal. Over the past years, continuous-wave (CW) mode-locked operation in the Nd:YLF crystal has been successfully realized with various methods [2–8]. However, high-power mode-locked Nd:YLF lasers with the pulse repetition rate up to several GHz have been scarcely demonstrated so far.

Passive mode locking with the semiconductor saturable absorber mirror (SESAM) is by far the most powerful technique to obtain the ultrashort pulses with the pulse repetition rate in the several hundred MHz range [9, 10]. To further increase the pulse repetition rate into the GHz region for the passively mode-locked laser, the main challenge is to overcome the tendency of the Q-switched mode locking, where the pulse train is modulated by the Q-switched envelop [11]. As a result, the SESAM usually needs to be intricately designed to have very small modulation depth (typically, below 1%) and low saturation fluence for achieving a multi-GHz passively mode-locked laser without the Q-switching instability, which undoubtedly increases the difficulties and costs in fabricating the SESAM. The extremely small modulation depth and low saturation fluence make it possible to utilize the nonlinear effect of the laser crystal itself as an alternative means for fulfilling a high-repetition-rate mode-locked laser. In fact, it was recently found that the third-order nonlinearity of the gain medium could be used to achieve a fairly stable multi-GHz operation in Nd-doped vanadate crystals with the mechanism of the self mode locking [12–14]. Such self-mode-locked mechanism relies on the fact that the number of the oscillated longitudinal modes in a multi-GHz mode-locked laser with the Nd-doped laser crystals to be characterized by the narrow gain bandwidth is not large, which is generally less than about 20 modes.

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Consequently, the third-order nonlinearity of the gain medium could offer enough locking strength to lock several tens of the oscillated longitudinal modes in a short cavity for accomplishing a high-repetition-rate mode-locked laser without any additional modulation elements except the gain medium inside the laser cavity, which is experimentally verified with our previous works [12–14]. It is worthwhile to point out that the previously reported high-repetition-rate self-mode-locked lasers were mainly focused on the performance at 1064 nm and 1342 nm. One of the attractive features of the Nd:YLF crystal is the emission lines at 1053 nm and 1047 nm. The 1053-nm line is inherently useful in developing a master oscillator for the Nd:glass power amplifier [15], while the 1047-nm line is found to play an important role in the skin wound healing [16]. Therefore, high-power high-repetition-rate mode-locked Nd:YLF lasers at 1053 nm and 1047 nm are highly desirable to be developed.

In this work, we report our experimental observations on a diode-pumped self-mode-locked Nd:YLF laser with multi-GHz pulse repetition rate for the first time. A novel approach that bases on the natural birefringence of a wedged Nd:YLF crystal and the alignment sensitivity of an optical resonator is utilized for efficient selection of the output polarization state. With the developed method, stable self-mode-locked operations with TEM_{00} transverse mode are accomplished for the σ- and π-polarization, respectively. At an incident pump power of 6.93 W, this compact pulsed laser produces output powers up to 2.15 W and 1.15 W at 1053 nm and 1047 nm under a pulse repetition rate of 2.717 GHz. We find that decreasing the separation between the gain medium and the input mirror brings in the pulse shortening thanks to the enhanced effect of the spatial hole burning (SHB), where the shortest pulse widths of 8 ps and 8.5 ps are obtained for the σ- and π-polarization, respectively. Furthermore, the occurrence of the second harmonic mode locking rather than the fundamental mode locking is experimentally observed when the gain medium is closely adjacent to the input mirror.

2. Experimental setup

The experimental setup for the diode-pumped self-mode-locked Nd:YLF laser is schematically sketched in Fig. 1. The input mirror was a concave mirror with the radius of curvature of 500 mm. It was antireflection (AR) coated at 806 nm on the entrance face, and was coated for high transmission at 806 nm as well as for high reflection at 1053 nm on the second surface. The gain medium was a 0.8 at. % a-cut Nd:YLF crystal with dimensions of 3 × 3 × 20 mm^3. Both facets of the laser crystal were AR coated at 806 nm and 1053 nm. Besides, the second surface of the gain medium was wedged at an angle $\theta_w = 3^\circ$ with respect to the first surface for efficient selection of the output polarization state as well as absolute elimination of the etalon effect. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper heat sink with the temperature of 16°C. The pump source was an 806-nm fiber-coupled laser diode with the core diameter of 400 μm and the numerical aperture of 0.14. The pump beam with the spot radius of approximately 200 μm was re-imaged inside the laser crystal with a lens set that has the focal length of 25 mm and the coupling efficiency of 90%. A flat wedged mirror with the reflectivity of 90% in the range of 1040-1060 nm was used as the output coupler during the experiment, which is experimentally found to allow for the maximum output power under the CW mode-locked circumstance and provide sufficient intracavity energy for stable self mode locking simultaneously. The optical cavity length was set to be about 55 mm, which corresponds to the free spectral range of 2.717 GHz. By using the ABCD-matrix theory, the cavity mode radius inside the laser crystal was calculated to be 230 μm. It should be mentioned that the stable self-mode-locked operation could be realized with the optical cavity length ranging from 45 mm to 100 mm, corresponding to the free spectral range of 1.5-3 GHz.

The real-time temporal behaviors of the mode-locked pulses were received by a high-speed InGaAs photodetector with the rise time of 35 ps, and the recorded signal was connected to a digital oscilloscope (Agilent, DSO 80000) with the electrical bandwidth of 12

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GHz and the maximum sampling interval of 25 ps. The output signal of the photodetector was also delivered to a radio frequency (RF) spectrum analyzer (Advantest, R3256A) with the bandwidth of 8 GHz. The fine structure of the mode-locked pulses was measured with the help of a commercial autocorrelator (APE pulse check, Angewandte Physik and Elektronik GmbH). A Fourier optical spectrum analyzer (Advantest, Q8347), which is constructed with a Michelson interferometer, was employed to monitor the spectral information with the resolution of 0.003 nm.

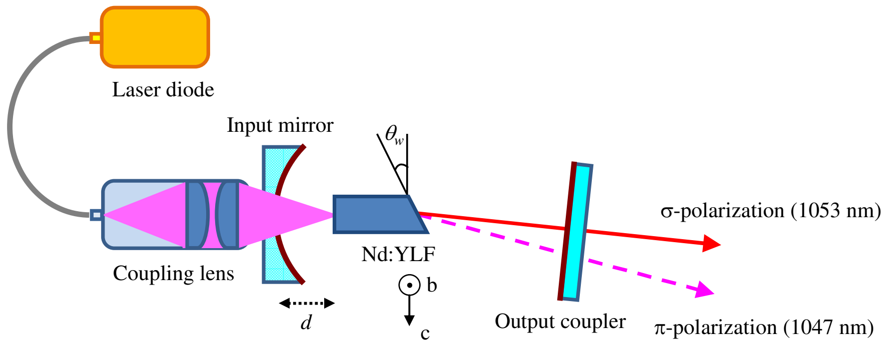

Fig. 1. Configuration of the cavity setup for the diode-pumped self-mode-locked Nd:YLF laser.

3. Performance of the self-mode-locked Nd:YLF laser

On the basis of the combined effect of the different deflection angle for the σ- and π-polarization due to the natural birefringence of a wedged laser crystal and the alignment sensitivity of an optical resonator, we experimentally verify that the output polarization state of the Nd:YLF laser could be switched simply by tilting the orientation of the output coupler [17]. Note that the σ- and π-polarization in the Nd:YLF crystal correspond to the emission lines at 1053 nm and 1047 nm, respectively. Then the Nd:YLF laser was finely adjusted to be in a steady CW mode-locked state by monitoring the real-time oscilloscope traces. The separation *d* between the laser crystal and the input mirror was initially set to be around 8 mm. At a pulse repetition rate of 2.717 GHz, the output powers for the CW mode locking at 1053 nm and 1047 nm as a function of the incident pump power at 806 nm are illustrated in Fig. 2. Note that the stable CW self-mode-locked operation could always be achieved as long as the incident pump power reaches the threshold. Meanwhile, the laser beam radius of 230 μm is larger than the pump beam radius of 200 μm in the present setup, which leads to a relatively large diffraction loss induced by the thermal lens aberration. Based on the assumption of a Gaussian-like pump profile and following the analysis in Ref [18], here we find that the combined effect of the mode size change in the laser crystal due to the Kerr self-focusing and the thermally induced diffraction loss could result in the nonlinear diffraction loss modulation on the order of 10^{-4}. This nonlinear loss modulation of the so-called thermo-Kerr mode locking is experimentally confirmed to be sufficient for the self-starting of the present self-mode-locked laser, where the required nonlinear loss modulation is numerically estimated to be around 10^{-5} [18]. Refer to the Fig. 2, the threshold pump powers at 1053 nm and 1047 nm are found to be almost the same. The maximum output power as high as 2.15 W is achieved for the σ-polarization, while the maximum output power for the π-polarization is 1.15 W. The two-dimensional spatial distributions at 1053 nm and 1047 nm under an incident pump power of 6.93 W were recorded with a digital camera, and both are found to display a near-diffraction-limited TEM_{00} transverse mode, as revealed in the inset of Fig. 2 for the case of the σ-polarization.

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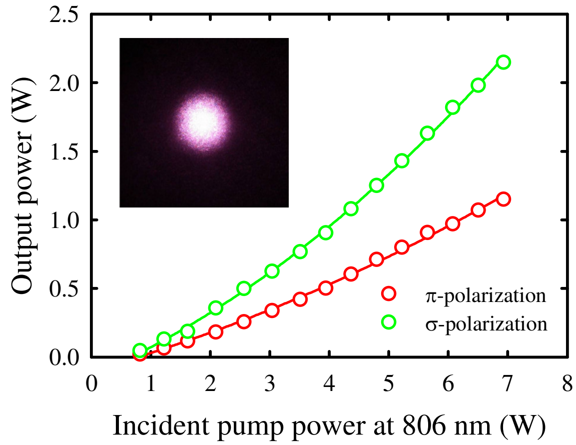

Fig. 2. Output powers for the CW mode locking at 1053 nm and 1047 nm as a function of the incident pump power at 806 nm, where the pulse repetition rate is 2.717 GHz. Inset: two-dimensional spatial distribution of the TEM_{00} transverse mode for the case of the σ-polarization.

Typical oscilloscope traces of the mode-locked pulses at 1053 nm are illustrated in Figs. 3(a)-3(b) with the time span of 1 μs and 5 ns, respectively. The amplitude fluctuation is experimentally found to be better than 2%. Moreover, the full modulation of the pulse trains without any CW background indicates that the complete mode locking is achieved in the current configuration. It is also worthwhile to mention that the Q-switched mode locking is not experimentally observed in the self-mode-locked Nd:YLF laser. For Q-switched mode locking, the period between the Q-switched envelops ranges from several hundreds of microsecond to several millisecond. However, the pulse train in millisecond time scale is not presented here because the temporal behavior could not be properly resolved with such wide time span owing to the reduction of the sampling rate. Therefore, we measure the RF spectrum to confirm the stability of the present self-mode-locked Nd:YLF laser, which is displayed in Figs. 3(c)-3(d). It can be seen clearly that the peak of the fundamental harmonic is 35 dBc above the background level, and the relaxation oscillation sidebands are negligibly observable. The stability of the laser is examined by the relative frequency deviation of the fundamental harmonic $\Delta\nu/\nu$, where ν is the central frequency and $\Delta\nu$ is the full width at half maximum (FWHM) of the fundamental harmonic, respectively. The relative frequency deviation of the fundamental harmonic is experimentally found to be around 10^{-5} over the day-long operation, which implies a nice long term stability.

On the other hand, Fig. 3(e) reveals the autocorrelation trace at 1053 nm. Assuming the temporal intensity to follow the Gaussian-shaped profile, the pulse width could be evaluated as 28.5 ps. Figure 3(f) depicts the corresponding optical spectrum with the central wavelength of 1053.34 nm and the FWHM of approximately 0.05 nm. As a result, the time-bandwidth product is estimated to be 0.424, which indicates the present pulses to be frequency chirped. Note that the mode spacing of 0.01 nm between the adjacent longitudinal modes is consistent with the fundamental harmonic of 2.717 GHz, as indicated in Fig. 3(f).

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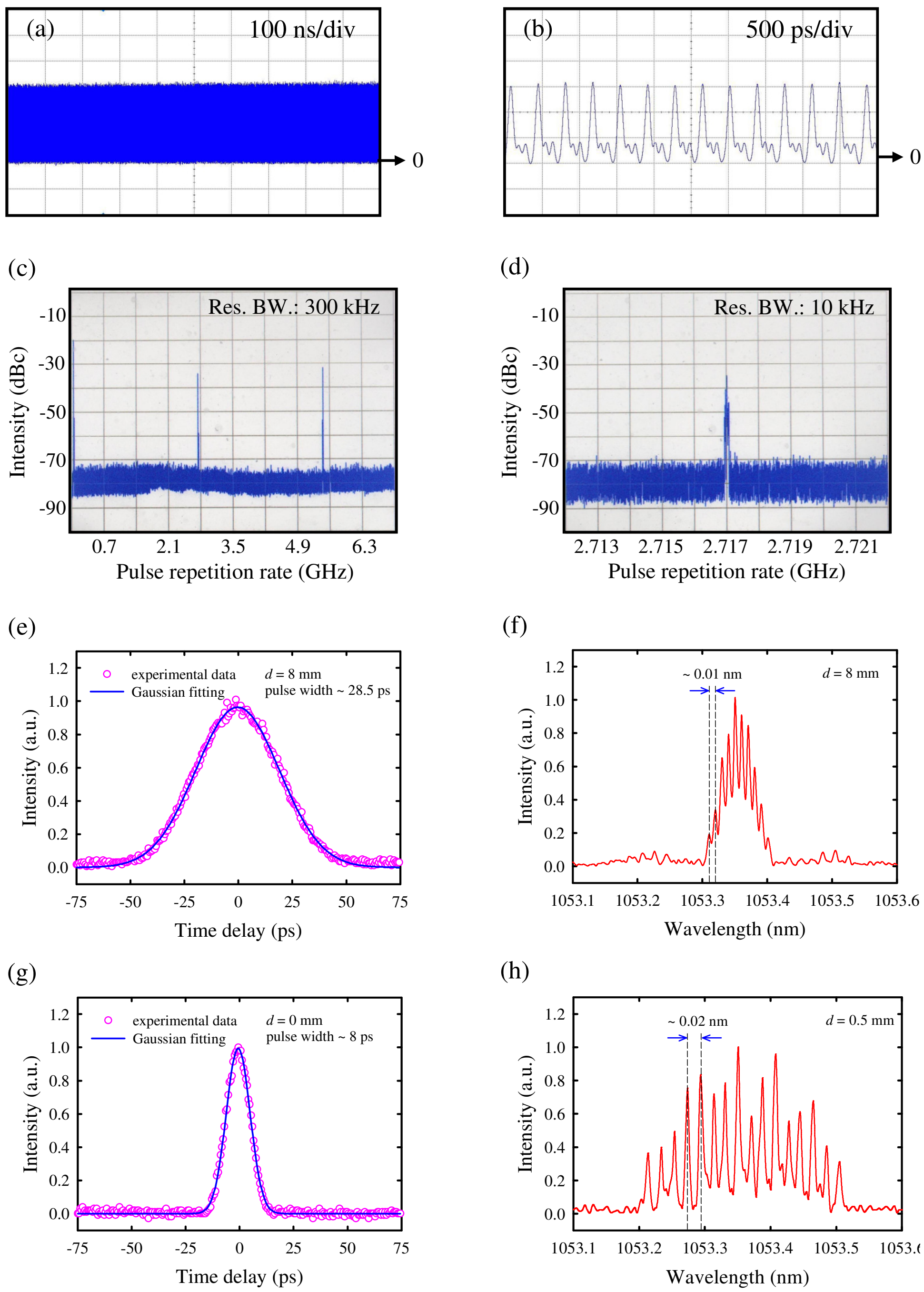

Fig. 3. Performance of the self-mode-locked Nd:YLF laser at 1053 nm: oscilloscope traces with the time span of (a) 1 μs and (b) 5 ns; RF spectrum with the frequency span of (c) 7 GHz and (d) 10 MHz; (e) autocorrelation trace for *d* = 8 mm; (f) optical spectrum for *d* = 8 mm; (g) autocorrelation trace for *d* = 0.5 mm; (h) optical spectrum for *d* = 0.5 mm.

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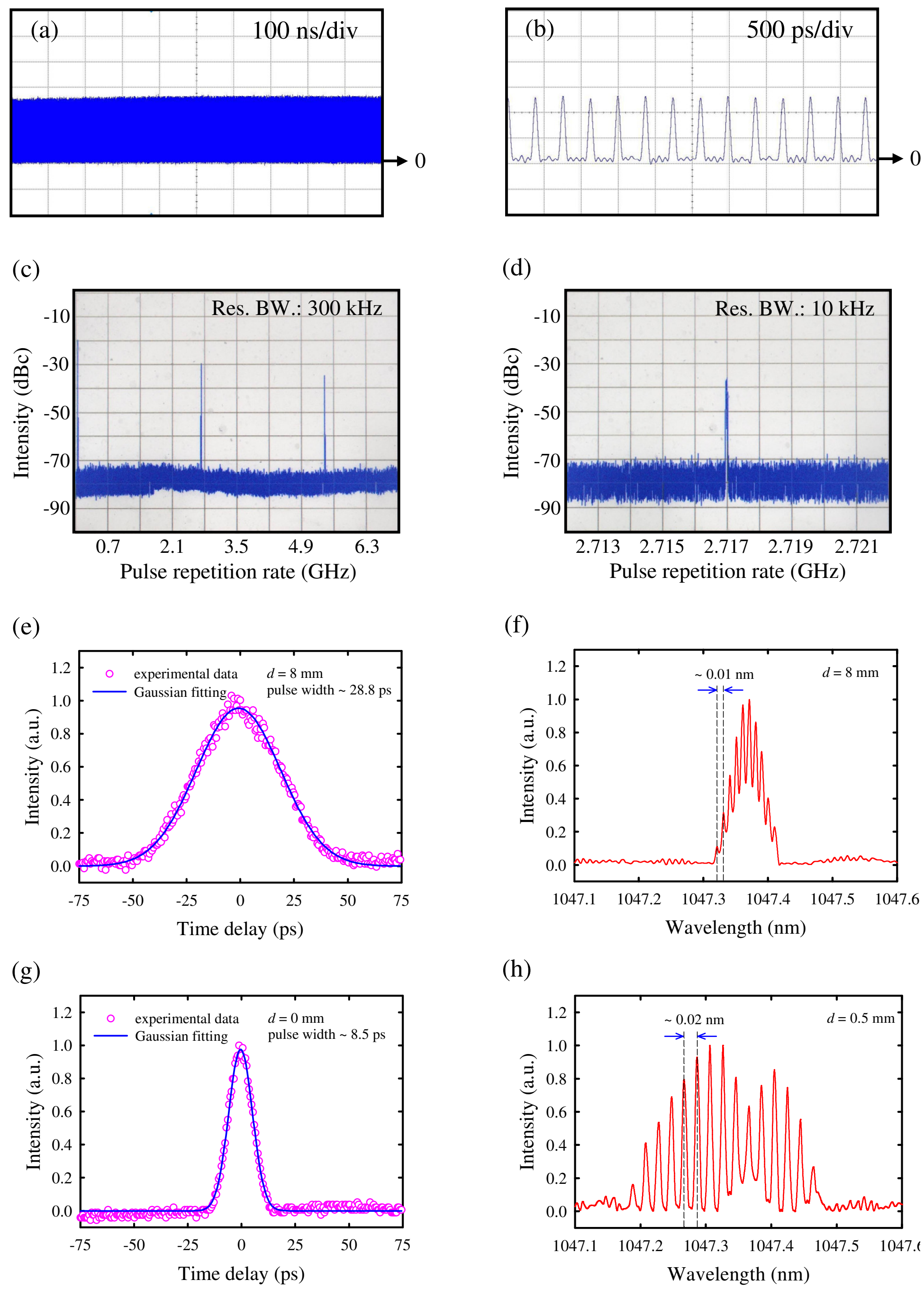

Fig. 4. Performance of the self-mode-locked Nd:YLF laser at 1047 nm: oscilloscope traces with the time span of (a) 1 μs and (b) 5 ns; RF spectrum with the frequency span of (c) 7 GHz and (d) 10 MHz; (e) autocorrelation trace for d = 8 mm; (f) optical spectrum for d = 8 mm; (g) autocorrelation trace for d = 0.5 mm; (h) optical spectrum for d = 0.5 mm.

Previous studies have theoretically analyzed and experimentally realized that decreasing the separation between the gain medium and the input mirror allows more longitudinal modes to oscillate in a standing-wave cavity [19–21]. Consequently, the SHB effect would be enhanced to lead the duration of the mode-locked pulse to be effectually shortened. In the

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present configuration, the pulse width of the mode-locked Nd:YLF laser is found to reduce continuously with decreasing the separation d between the gain medium and the input mirror. When the laser crystal is intimately next to the input mirror, i.e., d = 0.5 mm, the shortest pulse width of 8 ps is obtained at 1053 nm, as shown in Fig. 3(g). Figure 3(h) demonstrates the corresponding optical spectrum for d = 0.5 mm. It is obvious that the pulse shortening is accompanied with the spectral broadening due to the enhancement of the SHB effect. More intriguingly, the mode spacing between the adjacent longitudinal modes for d = 0.5 mm is found to be two times wider than that for d = 8 mm. The mode spacing of 0.02 nm corresponds to the pulse repetition rate of 5.434 GHz, which implies that the Nd:YLF laser changes the mode-locked status from the fundamental mode locking to the second harmonic mode locking. This observation might come from the fact that the locking strength due to the third-order nonlinearity is not strong enough to lock the phases of all lasing longitudinal modes with the mode spacing of 0.01 nm for d = 0.5 mm, in which the number of the oscillated longitudinal modes is estimated to be approximately 30 modes. In order to keep a stable self-mode-locked state within the large gain bandwidth supported by the enhanced SHB effect, it is experimentally found that the number of longitudinal modes would reduce by half with the longitudinal mode spacing to be doubled. This effectively introduces the effect of the spectral filtering to lead the Nd:YLF laser to operate at the second harmonic mode locking rather than the fundamental mode locking. This experimental result is never observed in our previous studies on the self-mode-locked lasers owing to the relatively narrow gain bandwidth in the Nd-doped vanadate crystals as compared with the Nd:YLF crystal [12–14].

Finally, the overall characteristics for the self-mode-locked Nd:YLF laser at 1047 nm are graphically summarized in Fig. 4. Generally speaking, the mode-locked performance for the π-polarization is found to be similar to the results obtained with the σ-polarization.

4. Conclusion

In summary, we have developed a novel technique that relies on the natural birefringence of a wedged laser crystal and the alignment sensitivity of an optical resonator to realize the reliable TEM_{00}-mode self-mode-locked lasers in the Nd:YLF crystal at 1053 nm and 1047 nm, respectively. It is experimentally found that the fundamental mode locking of the Nd:YLF laser could be reliably obtained with the tunable pulse repetition rate in the range of 1.5-3 GHz. At an incident pump power of 6.93 W and a pulse repetition rate of 2.717 GHz, this compact mode-locked laser produces the output powers up to 2.15 W and 1.35 W for the σ- and π-polarization, respectively. Furthermore, we have found that decreasing the separation between the laser crystal and the input mirror not only brings in the pulse shortening due to the enhancement of the SHB effect, where the shortest pulse durations at 1053 nm and 1047 nm are 8 ps and 8.5 ps, but also effectively introduces the effect of the spectral filtering to cause the Nd:YLF laser to operate at the second harmonic mode locking instead of the fundamental mode locking.

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