Dual-wavelength mode-locked Yb:YAG ceramic laser in single cavity

Hiroaki Yoshioka,1 Shinki Nakamura,1,* Takayo Ogawa,2 and Satoshi Wada2

1 Department of Media and Telecommunications Engineering, Faculty of Engineering, Ibaraki University,
4-12-1 Nakamaru-sawa, Hitachi, Ibaraki 316-8511, Japan
2 The Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
*Author email address: nakamura@mx.ibaraki.ac.jp

Abstract: We demonstrated a 380 fs dual-wavelength independently mode-locked Yb:YAG ceramic laser at 1033.6 and 1047.6 nm. To the best of our knowledge, this is the first dual-wavelength mode locking achieved in Yb-doped solid-state lasers.

©2010 Optical Society of America
OCIS codes: (140.4050) Mode-locked lasers; (140.3615) Laser, ytterbium.

1. Introduction

Dual-wavelength mode-locked pulses are attractive for double-pulse pump-probe measurements with a single source. In these applications, an exact synchronization of these two pulses is crucial. The operation of the dual-wavelength mode can also generate ultrashort pulses in the infrared region by difference-frequency mixing in nonlinear crystals. Furthermore, the synchronization and phase locking of separate femtosecond lasers have a strong impact on the precision frequency metrology based on optical frequency combs, providing the capability of a wide-bandwidth phase-coherent frequency network covering various spectral regions.

Some reports on dual-wavelength mode locking based on a single or double cavity were previously published [1-3]. Cross-mode locking has been achieved in a double-cavity dual-wavelength femtosecond Ti:sapphire laser, and synchronized 45-fs and 0.848-ps pulses at 810 and 785 nm have been generated [1]. The mode-locked Ti:sapphire laser based on self-spectrum splitting was achieved a simultaneously dual-wavelength operation at 738 and 752 nm in a single cavity [2]. As the dual-wavelength mode-locked operation using the other laser medium without Ti:sapphire, a dual-wavelength synchronously mode-locked Nd:CNGG laser was achieved simultaneously in a single cavity with a pulse duration of 5 ps at 1059.35 and 1061.71 nm [3].

In this paper, we report a dual-wavelength independently mode-locked Yb:YAG ceramic laser in a single cavity. To the best of our knowledge, this is the first dual-wavelength mode locking in Yb-doped solid-state lasers.

2. Experiment

The experimental setup for the dual-wavelength mode-locked Yb:YAG ceramic laser is shown in Fig. 1. A 940 nm fiber-coupled LD was used as a pumping source. The maximum pump power was 26.6 W. The 1-mm-thick Yb:YAG (C_yb = 9.8 at.%) ceramic plate was placed at Brewster’s angle between two high-reflectivity mirrors (M1, M2) that were antireflection (AR)-coated at 940 nm and had a high reflectivity at 1030 nm with a 100 mm radius of curvature (ROC). A 0.1% output coupler (OC) and a semiconductor saturable absorber mirror (SESAM, BATOP) with a 2% saturable absorption at 1030 nm were used for dual-wavelength mode locking in the respective arms. The total cavity length was 1620 mm. The laser beam was focused onto the SESAM by a concave mirror (M3, ROC = 250 mm). The angle of M3 was only modified from that in Ref. [4]. An SF10 Brewster prism pair (P1, P2) with a 465 mm separation was inserted in the other arm to compensate for the dispersion.

Experimentally, by a careful optimization of the cavity alignment (e.g., changing the distance and angle of the SESAM), the two independent dual-color pulses were then obtained. When the dual-wavelength mode locking was operated, two beams were measured and the dual-wavelength mode locking was observed in one of the beams. Figure 2 (a), (b) shows the intensity autocorrelation trace and spectrum of dual-wavelength mode-locked pulses. The
sech²-fitted pulse width was 380 fs. The spectral widths were 4.50 nm centered at 1033.6 nm and 3.08 nm centered at 1047.6 nm. These result in time-bandwidth products of 0.480 at the wavelength of 1033.6 nm and 0.321 at the wavelength of 1047.6 nm. The time-bandwidth product of 0.480 at the wavelength of 1033.6 nm increased by 52% from the Fourier limit for a sech² pulse (0.315). This indicates that two dual-color autocorrelation traces combined and the large time-bandwidth product at 1033.6 nm was calculated using longer pulses at 1047.6 nm. On the other hand, the small time-bandwidth product at the wavelength of 1047.6 nm was calculated using shorter pulses at 1033.6 nm. The average output power was 8 mW at a pump power of 26.6 W. The repetition rate was 91 MHz.

Figure 2 (c) shows the expected transform-limited pulses obtained by an inverse Fourier transformation of (i) the dual wavelength that is assumed to operate one mode locking with the spectrum between 1033.6 and 1047.6 nm, and the separated wavelengths at (ii) 1033.6 nm and (iii) 1047.6 nm. The full widths at half maximum (FWHMs) of the numerically obtained pulse duration are $t_p = 115, 298$ and $341$ fs for Figs. 2 (c)-(i) – 2 (c)-(iii), respectively. The pulse width in Fig. 2 (c)-(i) is 70% below the measured pulse width (380 fs) of the dual-wavelength mode locking in Fig. 2 (a), and the pulse duration of Fig. 2 (c)-(i) has two large pedestals. These pedestals were not quenched in the case including a large group-delay dispersion. On the other hand, the pulse widths in Figs. 2 (c)-(ii) and 2 (c)-(iii) are respectively 22% and 10% below the measured pulse width (380 fs) of the dual-wavelength mode locking in Fig. 2 (a); these values are close to the measured dual-wavelength pulse width of 380 fs. These results indicate that the measured dual-wavelength mode locking was independently operated between 1033.6 and 1047.6 nm.

The synchronization of dual-wavelength ultrashort pulses induced the generation of ultrahigh-repetition-rate pulses by optical beating [3, 5]. Furthermore, the XPM that induced cross-mode locking in a dual-wavelength femtosecond laser caused self-synchronization with a timing jitter of a few femtoseconds [6]. In our dual-wavelength mode locking, no generation of ultrahigh-repetition-rate pulses by optical beating or XPM was observed. This indicates that our dual-wavelength mode locking was independently operated at 1033.6 and 1047.6 nm.

3. Conclusion

A dual-wavelength femtosecond Yb:YAG ceramic laser was demonstrated. We successfully achieved simultaneous independent generation of mode locking on the two strongest gain lines of the laser, centered at 1033.6 and 1047.6 nm wavelengths. Each pulse width was measured to be approximately 380 fs using an autocorrelator. The spectral widths were 4.50 nm centered at 1033.6 nm and 3.08 nm centered at 1047.6 nm. The pulse widths were obtained by inverse Fourier transformation as to be 298 and 341 fs for the separated wavelength at 1033.6 and 1047.6 nm, respectively. By assuming that the two wavelengths generate one pulse, the pulse width was obtained by inverse Fourier transformation as 115 fs. These results indicate that the measured dual-wavelength mode locking was independently operated between 1033.6 and 1047.6 nm. To the best of our knowledge, this is the first dual-wavelength mode locking achieved in Yb-doped solid-state lasers.

3. References

[1] C. J. Zhu, J. F. He, and S. C. Wang, Opt. Lett. 30, 561-563 (2005).
[2] Z. Zhang, and T. Yagi, Opt. Lett. 18, 2126-2128 (1993).
[3] G. Q. Xie, D. Y. Tang, H. Luo, H. J. Zhang, H. H. Yu, J. Y. Wang, X. T. Tao, M. H. Jiang, and L. J. Qian, Opt. Lett. 33, 1872 (2008).
[4] H. Yoshioka, S. Nakamura, T. Ogawa, and S. Wada, Opt. Express 17, 8919-8925 (2009).
[5] M. D. Pelusi, H. F. Liu, D. Novak, and Y. Ogawa, Appl. Phys. Lett. 71, 449-451 (1997).
[6] A. Leitenstorfer, C. Fürst, and A. Laubereau, Opt. Lett. 20, 916-918 (1995).