Femtosecond pulse operation of a Tm,Ho-codoped crystalline laser near 2 μm

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We demonstrate, for the first time to our knowledge, femtosecond-regime mode locking of a Tm,Ho-codoped crystalline laser operating in the 2 μm spectral region. Transform-limited 570 fs pulses were generated at 2055 nm by a $\mathrm{Tm,Ho:KY(WO_4)_2}$ laser that produced an average output power of 130 mW at a pulse repetition frequency of 118 MHz. Mode locking was achieved using an ion-implanted InGaAsSb quantum-well-based semiconductor saturable absorber mirror. © 2010 Optical Society of America

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In recent years crystalline bulk and amorphous fiber media with $\mathrm{Tm^{3+}}$ and/or $\mathrm{Ho^{3+}}$ dopant ions have been shown to be excellent candidate gain materials for high-power and broadly tunable 2 μm lasers that can also be used for ultrashort pulse generation. Ultrafast laser sources around 2 μm are of particular interest for applications in time-resolved spectroscopy, nonlinear frequency upconversion to the mid- and far-IR spectral regions [1], mid-IR supercontinuum generation [2], optical communications, and photomedicine [3]. Moreover, ultrafast 2 μm lasers can be used for 3-D microstructuring [4] of semiconductor materials where standard 1 μm sources based on Ti:sapphire or Yb-doped lasers are not appropriate. Despite the earlier demonstrations of mode-locked thulium-fiber lasers, these systems still operate at relatively low average powers, usually in the range of few tens of milliwatts where stable mode locking is achievable [5–7]. Only recently, a Tm-doped fiber laser producing 1.7 ps pulses at an average power of 178 mW was demonstrated using an additive-pulse mode-locking technique [8] and, alternatively, 108 fs pulses at 1980 nm with an average power of 3.1 W were produced after amplification of Raman-shifted Er-doped fiber laser in a Tm-doped fiber [9].

By contrast, $\mathrm{Tm^{3+}}$-doped and $\mathrm{Tm^{3+},Ho^{3+}}$-codoped crystalline gain media offer attractive alternative design strategies for high-power ultrashort pulse generation in the 2 μm spectral region [10–12]. Such lasers can be pumped directly by well-developed high-power laser diodes around 800 nm or, in case of Ho-doped gain media, can be in-band pumped using Tm-based crystalline or fiber lasers [13]. Although a number of such high-power and broadly tunable lasers have been reported for cw operation, relatively few have been employed for ultrashort pulse generation. Specifically, with active mode locking, pulses of 35 ps and 100 ps duration were generated from Tm:YAG [14] and $\mathrm{Tm-Ho:BaY_2F_8}$ [15] lasers having average powers of 20 mW and 70 mW, respectively. More recently, passively mode-locked $\mathrm{Tm:KLu(WO_4)_2}$ [16] and $\mathrm{Tm,Ho:KY(WO_4)_2}$ (Tm,Ho:KYW) [17] lasers have been demonstrated using carbon nanotubes and InGaAsSb-based saturable absorbers, and these produced 9.7 ps and 3.3 ps pulses near 1950 nm and 2060 nm, respectively.

Here we report further progress in the development of ultrashort-pulse 2 μm lasers. Specifically, a Tm,Ho:KYW laser that delivers transform-limited 570 fs pulses at 2055 nm has been demonstrated. An average output power up to 130 mW was produced in stable mode locking at a pulse repetition frequency of 118 MHz.

The assessments of this laser were performed with a Tm(5 at. %),Ho(0.4 at. %)-codoped KYW crystal [18]. This gain element, having a Brewster-cut geometry, was 1.5 mm in length and was oriented in the cavity for optical propagation along the $b(N_p)$-axis and for a polarization along the N_m crystallo-optic axis. An asymmetric z-fold resonator was configured with two folding mirrors $\mathrm{M_1}$ and $\mathrm{M_2}$ having radii of curvature of 75 mm and 100 mm, respectively, an output coupler (OC) with 1% transmission around 2 μm, and a high-reflectivity mirror (HR) or semiconductor saturable absorber mirror (SESAM) (Fig. 1). The laser beam mode radii inside the gain crystal were calculated to be 23×46 μm. A Ti:sapphire laser

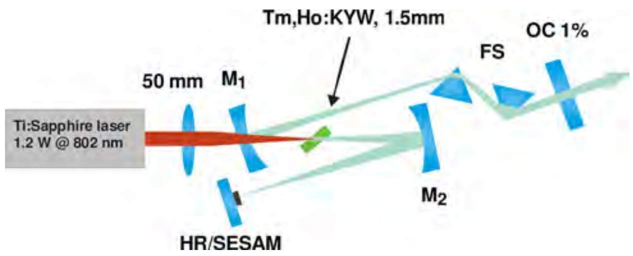

Fig. 1. (Color online) Setup of the Tm,Ho:KYW mode-locked laser. $\mathrm{M_1}$ and $\mathrm{M_2}$, plano-concave high-reflector mirrors ($r_1=-75$ mm, $r_2=-100$ mm); OC, output coupler ($T=1\%$ at 2000 nm); HR, plane high-reflector mirror; FS, pair of IR fused-silica prisms.

producing 1.2 W of output power at 802 nm was used as a pump source, and its beam was focused into the gain medium via a 50 mm focal length lens to a spot radius of 23.5 μm ($1/e^2$ intensity) measured in the air at the location of the gain crystal. During cw operation this laser produced a maximum output power of 472 mW at 2057 nm and operated with a slope efficiency of 41%. When two fused-silica prisms were inserted into the long arm of the cavity, the output power reduced to 330 mW. A prism pair was used for intracavity dispersion control through a glass material dispersion of ~ -113 fs^2/mm at 2060 nm.

The SESAM structure used for the initiation and stabilization of passive mode locking in the Tm,Ho:KYW laser was similar to that described in [17] and incorporated a GaSb/AlAsSb distributed Bragg reflector having a high reflectivity at ~1930–2150 nm and 2 × InGaAsSb quantum wells as the absorber. In our previous work we demonstrated 3.3 ps pulses centerd on 2057 nm from a Tm,Ho:KYW laser using this as-grown SESAM. However, it was found that no significant variations in pulse durations or spectral widths were observed for different values of intracavity pulse energy or net cavity group-velocity dispersion, and we attributed this type of mode-locking regime to the relatively long recovery time (>100 ps) and low self-amplitude modulation in the as-grown SESAM. To decrease the carrier recombination time [19,20], the SESAM samples were irradiated with 4 MeV As$^+$ ions at doses ranging from 5×10^{10} cm^{-2} to 5×10^{11} cm^{-2}. As the implantation dose increased, we observed a damage-induced reduction of the overall reflectivity as depicted in Fig. 2. For the sample irradiated with a 5×10^{10} cm^{-2} dose, we estimate this loss to be around 1%.

When the SESAM structure, which was implanted with a 5×10^{10} cm^{-2} dose, was inserted into the short arm of the cavity, where the calculated mode radius was 140 μm, the laser produced up to 150 mW of average output power. Following suitable subsequent minor adjustment of M_2 mirror position, stable mode locking was realized at 2055 nm with a maximum average output of 130 mW and a pulse repetition frequency of 118 MHz. This stable ultrashort-pulse operation was observed when the Tm,Ho:KYW laser produced average powers throughout the range of 31–130 mW, whereas Q-switched mode locking became evident at lower intracavity powers, specifically, when the fluence on the SESAM was below 42.7 μJ/cm^2 (Fig. 3). The pulse durations varied from 2.64 ps at the mode locking threshold to 570 fs at the maximum output power of 130 mW [Figs. 4(a) and 4(b)]. The pulses were near-transform-limited with time-bandwidth products in the 0.31–0.32 range. Figure 4(c) shows the pulse durations as a function of the intracavity pulse energy E_p at a constant negative dispersion D in the laser cavity of -1950 fs^2 per round trip. It can be seen that the measured pulse duration decreased inversely in proportion to E_p according to the expression

$$\tau_p = 1.7627 \frac{2|D|}{\delta_L E_p},$$

where δ_L is the self-phase modulation (SPM) coefficient, as predicted from a soliton mode-locking model [21]. The best fit to the experimental data applied when $\delta_L = 1.2 \times 10^{-7}$ W^{-1}. This value in good agreement with that obtained ($\delta_L = 1.16 \times 10^{-7}$ W^{-1}) from the measurements of pulse duration as a function of the intracavity dispersion, which was varied by increasing the insertion of one prism at constant intracavity pulse energy of 95 nJ, when $d\tau_p/d|D|$ parameter was found to be 0.32 fs^{-1}. The data deduced for the SPM coefficient can provide an estimate for the nonlinear refractive index, n_2, of the gain medium according to the expression

$$\delta_L = \frac{2\pi}{\lambda} n_2 \frac{2L_g}{A_{\text{eff}}},$$

where λ is the laser wavelength, L_g is the length of the gain medium, and A_{eff} is the mode area in the laser crystal. The n_2 of Tm,Ho:KYW at 2055 nm was thus calculated to be 1.57×10^{-16}cm^2/W. Previously, the nonlinear refractive index of Yb^{3+}:KYW was measured to be 8.7×10^{-16}cm^2/W at 1080 nm [22].

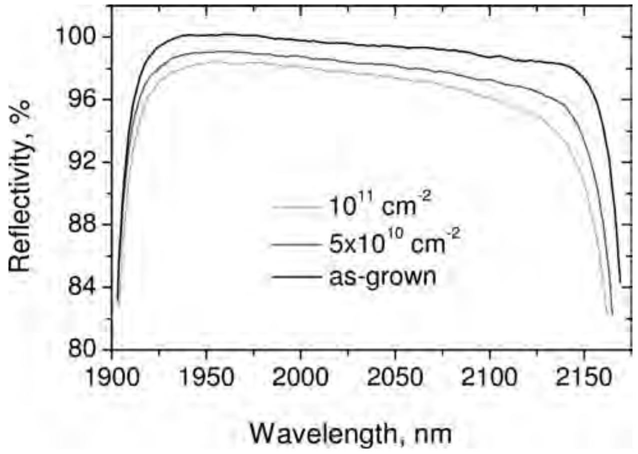

Fig. 2. Reflectivity curves of the implanted and non-implanted SESAM structures.

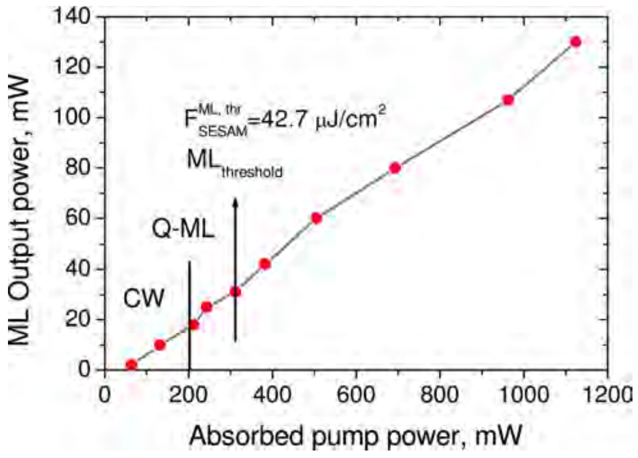

Fig. 3. (Color online) Input-output characteristics of the mode-locked Tm,Ho:KYW laser at 2055 nm.

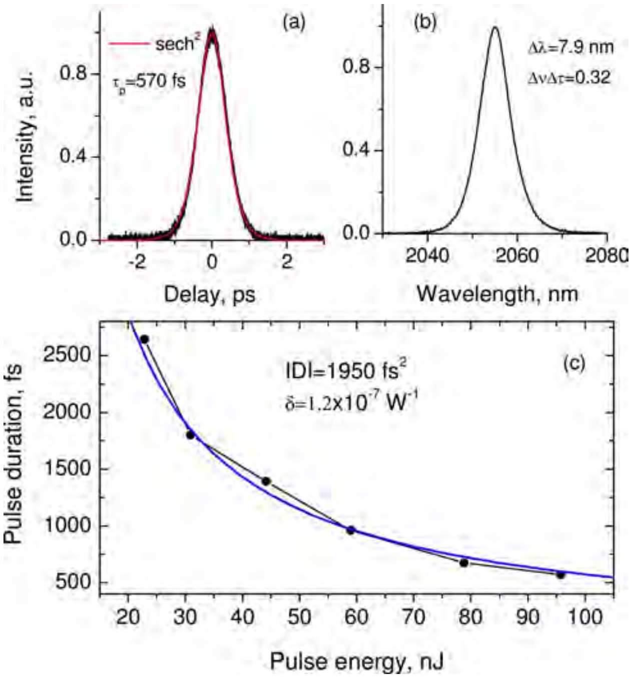

Fig. 4. (Color online) (a) Intensity autocorrelation and (b) spectrum of the shortest pulses obtained from the mode-locked Tm,Ho:KYW laser. (c) Dependence of the pulse duration on the intracavity pulse energy. The solid (blue online) curve is a fit to $1/E_p$.

It is noteworthy to state that similar mode-locking parameters were obtained using an SESAM that had been ion implanted at a higher dosage level of 10^{11} cm^{-2}. The key difference was that of a lower output power of 90 mW that implies higher nonsaturable losses in the absorber.

In conclusion, we have demonstrated a passively mode-locked Tm,Ho:KYW laser operating around 2055 nm. Pulse durations in the range of 2.64–0.57 ps were generated with corresponding average output powers of 31–130 mW at a pulse repetition frequency of 118 MHz. Soliton mode locking was achieved by deploying an ion-implanted InGaAsSb quantum-well-based SESAM and a pair of fused-silica prisms for the dispersion control. Ongoing work is being concentrated on the development of diode-pumped Tm,Ho-codoped femtosecond lasers using SESAMs having better optimized macroparameters for efficient femtosecond mode locking in the 2 μm spectral region.

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References

1. M. A. Watson, M. V. O'Connor, D. P. Shepherd, and D. C. Hanna, Opt. Lett. **28**, 1957 (2003).
2. J. H. V. Price, T. M. Monro, H. Ebendorff-Heidepriem, F. Poletti, P. Horak, V. Finazzi, J. Y. Y. Leong, P. Petropoulos, J. C. Flanagan, G. Brambilla, X. Feng, and D. J. Richardson, IEEE J. Quantum Electron. **13**, 738 (2007).
3. D. Theisen, V. Ott, H. W. Bernd, V. Danicke, R. Keller, and R. Brinkmann, Proc. SPIE **5142**, 96 (2003).
4. R. R. Gattass and E. Mazur, Nat. Photonics **2**, 219 (2008).
5. L. E. Nelson, E. P. Ippen, and H. A. Haus, Appl. Phys. Lett. **67**, 19 (1995).
6. R. C. Sharp, D. E. Spock, N. Pan, and J. Elliot, Opt. Lett. **21**, 881 (1996).
7. M. A. Solodyankin, E. D. Obraztsova, A. S. Lobach, A. I. Chernov, A. V. Tausenev, V. I. Konov, and E. M. Dianov, Opt. Lett. **33**, 1336 (2008).
8. M. Engelbrecht, F. Haxsen, A. Ruehl, D. Wandt, and D. Kracht, Opt. Lett. **33**, 690 (2008).
9. G. Imeshev and M. E. Fermann, Opt. Express **13**, 7424 (2005).
10. X. Mateos, V. Petrov, J. Liu, M. C. Pujol, U. Griebner, M. Aguiló, F. Diaz, M. Galan, and G. Viera, IEEE J. Quantum Electron. **42**, 1008 (2006).
11. N. Coluccelli, G. Galzerano, P. Laporta, F. Cornacchia, D. Parisi, and M. Tonelli, Opt. Lett. **32**, 2040 (2007).
12. X. Han, J. M. Cano-Torres, M. Rico, C. Cascales, C. Zaldo, X. Mateos, S. Rivier, U. Griebner, and V. Petrov, J. Appl. Phys. **103**, 083110 (2008).
13. B. Yao, X. Duan, L. Zheng, Y. Ju, Y. Wang, G. Zhao, and Q. Dong, Opt. Express **16**, 14668 (2008).
14. J. F. Pinto, L. Esterowitz, and G. H. Rosenblatt, Opt. Lett. **17**, 731 (1992).
15. G. Galzerano, M. Marano, S. Longhi, E. Sani, A. Toncelli, M. Tonelli, and P. Laporta, Opt. Lett. **28**, 2085 (2003).
16. W. B. Cho, A. Schmidt, J. H. Yim, S. Y. Choi, S. Lee, F. Rotermund, U. Griebner, G. Steinmeyer, V. Petrov, X. Mateos, M. C. Pujol, J. J. Carvajal, M. Aguiló, and F. Daz, Opt. Express **17**, 11007 (2009).
17. A. A. Lagatsky, F. Fusari, S. Calvez, G. A. Gupta, V. E. Kisel, N. V. Kuleshov, C. T. A. Brown, M. D. Dawson, and W. Sibbett, Opt. Lett. **34**, 2587 (2009).
18. A. A. Lagatsky, F. Fusari, S. V. Kurilchik, V. E. Kisel, A. S. Yasukevich, N. V. Kuleshov, A. A. Pavlyuk, C. T. A. Brown, and W. Sibbett, Appl. Phys. B **97**, 321 (2009).
19. E. L. Delpon, J. L. Oudar, N. Bouche, R. Raj, A. Shen, N. Stelmakh, and J. M. Lourtioz, Appl. Phys. Lett. **72**, 759 (1998).
20. J. W. Tomm, V. Strelchuk, A. Gerhardt, U. Zeimer, M. Zorn, H. Kissel, M. Weyers, and J. Jimenez, J. Appl. Phys. **95**, 1122 (2004).
21. U. Keller, Prog. Opt. **46**, 1 (2004).
22. K. V. Yumashev, N. N. Posnov, P. V. Prokoshin, V. L. Kalashnikov, F. Mejid, I. P. Poloyko, V. P. Mikhailov, and V. P. Kozich, Opt. Quantum Electron. **32**, 43 (2000).