Passive mode locking of a $Tm,Ho:KY(WO_4)_2$ laser around 2 μm

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We report the first demonstration, to our knowledge, of passive mode locking in a Tm^{3+}, Ho^{3+}-codoped $KY(WO_4)_2$ laser operating in the 2000–2060 nm spectral region. An InGaAsSb-based quantum well semiconductor saturable absorber mirror is used for the initiation and stabilization of the ultrashort pulse generation. Pulses as short as 3.3 ps were generated at 2057 nm with average output powers up to 315 mW at a pulse repetition frequency of 132 MHz for 1.15 W of absorbed pump power at 802 nm from a Ti:sapphire laser. © 2009 Optical Society of America

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Ultrashort-pulse lasers operating in the 2 μm spectral region are of particular interest for applications in time-resolved spectroscopy, nonlinear frequency upconversion to the mid- and far-infrared wavelengths, optical communications, and photomedicine. To date different laser sources have been realized for generation of ultrashort pulses that are tunable around 2 μm. Amongst the options available, Tm- and Tm:Ho-doped fiber [1,2] and crystalline laser sources [3,4] operating in the ~1800–2100 nm range and Cr^{2+}-doped chalcogenide lasers [5,6] at around 2400 nm have gained precedence. Pulses as short as 500 and 190 fs have been produced from Tm-fiber lasers by implementing either additive-pulse mode locking [1] or by using an InGaAs semiconductor saturable absorber mirror (SESAM) [2]. More recently, Tm-doped and Tm:Ho-codoped ultrashort pulse fiber lasers passively mode locked by Sb-based SESAMs or carbon nanotube saturable absorbers have been demonstrated, and these produced average powers of up to few tens of milliwats [7–9]. Despite attractive features such as compactness and reliability of operation of fibre laser sources, they suffer from the low average powers at which stable mode locking is achievable. By contrast, Tm^{3+}-doped and Tm^{3+},Ho^{3+}-codoped crystalline gain media offer attractive alternative design strategies for high-power, efficient, and broadly tunable lasers for the 2 μm spectral region [10–14], and these can be configured for ultrashort-pulse generation with appropriate mode locking techniques. The Tm^{3+} ion when hosted in the most crystalline and amorphous materials exhibits strong absorption bands around 800 nm and thus can be pumped efficiently by low-cost and high-power AlGaAs laser diodes. By comparison, Cr^{2+}-doped chalcogenide laser systems require more expensive pump lasers that operate around 1.6 μm. Although a number of high-power and broadly tunable 2 μm Tm- and Tm:Ho-doped crystalline lasers have been reported, only a few have been employed for ultrashort pulse generation, and for these an active mode locking technique was deployed. Pulses as short as 35 and 100 ps from Tm:YAG [3] and $Tm-Ho:BaY_2F_8$ [4] lasers with average powers of 20 and 70 mW, respectively, have been obtained.

Here we report, for the first time to our knowledge, a $Tm^{3+},Ho^{3+}:KY(WO_4)_2$ (Tm,Ho:KYW) laser that is passively mode locked in the 2000–2060 nm spectral range using a Sb-based SESAM.

A schematic of the laser setup is depicted in Fig. 1. The laser-related performance assessments of Tm,Ho:KYW were made by using a highly asymmetric Z-fold laser cavity that was configured with two folding mirrors, M1 and M2, having radii of curvature of 75 and 100 mm, respectively, an output coupler (OC) with 1% transmission around 2 μm and a high-reflectivity mirror (HR) or SESAM. In the cavity configuration used the laser beam mode radii inside the gain crystal were 23×46 μm. A Ti:sapphire laser producing 1.2 W of output power at 802 nm was used

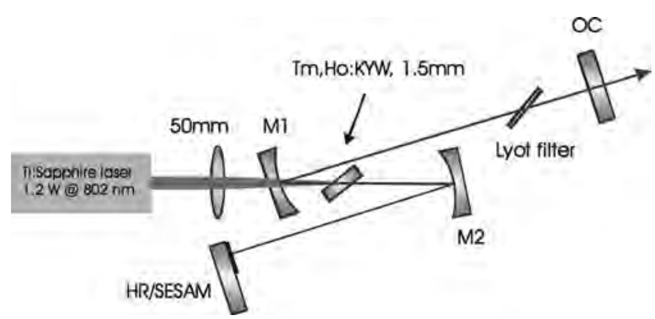

Fig. 1. Schematic diagram of the passively mode locked Tm,Ho:KYW laser. M1, M2, plano-concave high-reflector mirrors (r_1=−75 mm, r_2=−100 mm); OC, output coupler (T=1% at 2000 nm). Cavity parameters: OC-M1 separation, 800 mm; M1–crystal–M2 separations, 38 and 63 mm; M2–SESAM separation, 233 mm; M1, M2 mirror folding angles, 8°.

as a pump source, and its beam was focused into the gain medium by a 50 mm focal length lens to a spot radius of 23.5 μm ($1/e^2$ intensity) measured in the air at the position of gain crystal. The gain medium consists of a 1.5-mm-long Brewster-cut KYW crystal codoped with 5 at. % of Tm^{3+} and 0.4 at. % of Ho^{3+} [15,16]. The crystal was oriented in the cavity for propagation along the $b(N_p)$ axis and for polarization along the N_m crystallo-optic axis. During continuous wave operation (the short cavity arm was terminated by high-reflector dielectric mirror) this Tm,Ho:KYW laser produced an output power of 430 mW at 2057 nm from 1.15 W of absorbed pump power, had a threshold of 50 mW of absorbed pump power, and operated with a slope efficiency of 40% (Fig. 2). Using a 2-mm-thick quartz plate as a Lyot tuning filter with its optical axis in the plane of the input face, laser operation was obtained over the 1890–2080 nm range, within which a maximum output power of 390 mW was obtained at 2057 nm (Fig. 2, inset). It should be noted that the measured tunability range of the Tm,Ho:KYW laser extends beyond the 2 μm spectral region where, we believe, Tm^{3+} partially contributed to the laser output, since the tunability range of the Tm:KYW laser was previously measured to be 1800–2010 nm. The tunability around 1960 nm region was not continuous, which can be attributed to the laser beam interaction with the water vapor.

The SESAM used for the initiation and stabilization of passive mode locking in the Tm,Ho:KYW laser incorporated a distributed Bragg reflector structure and InGaAsSb quantum well layers to perform the functions of a saturable absorber. The distributed Bragg reflector structure comprised 20 pairs of 128.65-nm-thick (λ/4) GaSb and 154.52-nm-thick (λ/4) $AlAs_{0.0834}Sb$ layers grown on a 500-μm-thick Te-doped GaSb(100) substrate. The absorber region was added as the topmost quarter-wave, high-index portion of the mirror stack and consisted of two 5.5-nm-thick $In_{0.4}Ga_{0.6}As_{0.14}Sb_{0.86}$ quantum wells separated by a 20-nm-thick $Al_{0.24}Ga_{0.76}As_{0.021}Sb_{0.979}$ layer and surrounded by $Al_{0.24}Ga_{0.76}As_{0.021}Sb_{0.979}$. The structure had a reflectivity of 99.9%–98.2% in the 1960–2125 nm spectral range, and the quantum wells photoluminescence peak was at around 2100 nm (Fig. 3). The additional peak in the emission spectrum at 2145 nm is attributed to the quantum wells photoluminescence enhanced by the end of the mirror stopband.

A stable mode-locked operation of this Tm,Ho:KYW laser was realized when the plane high-reflectivity mirror terminating the cavity short arm was replaced by the SESAM structure where the cavity beam mode size was designed to be 82 μm in radius. This passively mode-locked Tm,Ho:KYW laser produced a maximum output power of 315 mW at 2057 nm and had a mode locking threshold of 350 mW of absorbed pump power, at which 63 mW of average output power was produced. The generated pulse duration was measured by using the pulse intensity autocorrelation technique, implying a Si-based detector working in two-photon absorption regime. The shortest pulse durations were deduced to be 3.3 ps, assuming sech^2 intensity profiles (Fig. 4), and the corresponding spectral width of 1.3 (±0.15) nm implied a duration–bandwidth product of 0.3 (±0.035) (Fig. 4, inset). The microwave spectrum shows a clean peak at a repetition rate of 132.25 MHz with no side peaks, thus confirming the absence of Q-switching instabilities (Fig. 5), and the wide-span measurements (Fig. 5, inset) indicate a single-pulse operation. The corresponding intracavity fluences on the SESAM during these conditions of stable mode locking were in the range of 1130–225 $\mu J/cm^2$, whereas a Q-switching instability was evident at fluences on the saturable absorber in the range of 220–100 $\mu J/cm^2$. It should be noted that when two intracavity fused-silica prisms were used for the dispersion control (group-delay dispersion has reached $-1100\ fs^2$ around 2060 nm), no significant variations in pulse durations or spectral widths were observed for different values of the net cavity dispersion. In this context, relatively long pulse durations would be attributed to the nonoptimized parameters of the saturable absorber, notably, small modulation depth (<0.8%) and relatively long recovery time (~100 ps). To investigate the tunability of the Tm,Ho:KYW laser during passive mode locking, a 2-mm-thick Lyot filter was inserted into the long arm of the cavity. In this case, the mode-locked output

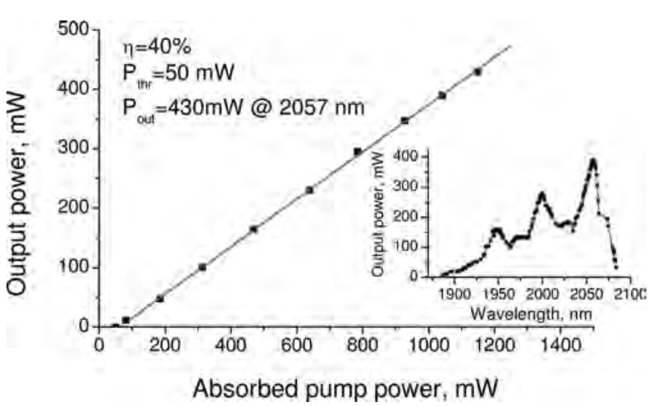

Fig. 2. Input–output characteristics of the Tm,Ho:KYW laser during cw operation. Inset, tunability of the Tm,Ho:KYW laser at maximum pump power of 1.2 W.

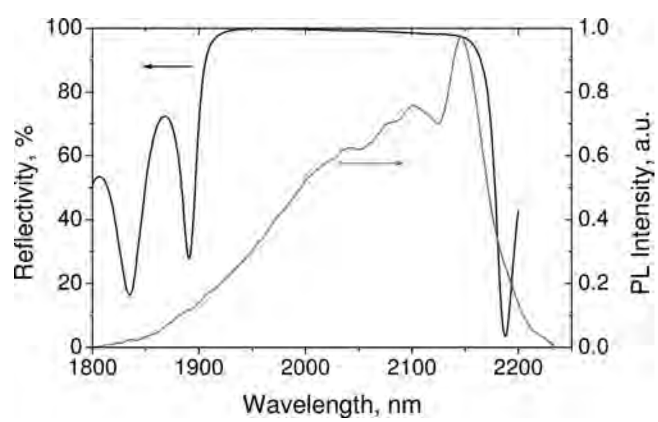

Fig. 3. Reflectivity curve of the InGaAsSb quantum well SESAM (left axis) and the quantum wells luminescence spectrum recorded at room temperature.

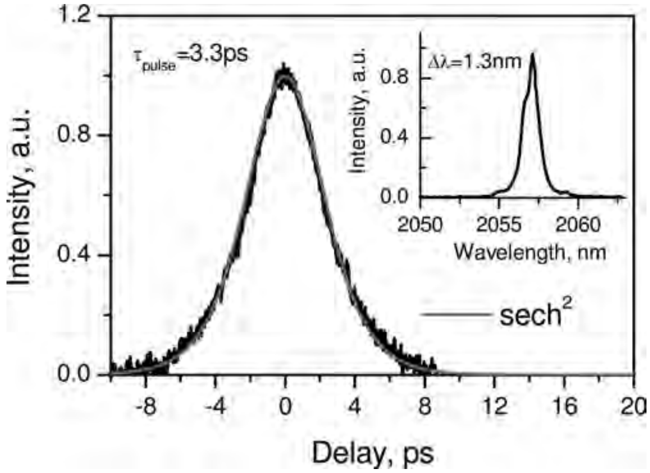

Fig. 4. Intensity autocorrelation trace of the laser pulses from the Tm,Ho:KYW laser (gray curve is a fit assuming $sech^2$ pulse shapes). Inset, corresponding optical spectrum. The time–bandwidth product is 0.3.

could be tuned from 2000 to 2060 nm with the pulse durations ranging from 5.1 ps (around 2056 nm where 300 mW of average power was generated) to 7 ps at the maximum average output power level of 200 mW obtained at 2000 nm.

In conclusion, passive mode locking in the Tm,Ho:KYW laser has been demonstrated by using an InGaAsSb-based SESAM. Pulse durations as short as 3.3 ps were achieved at 2056 nm at a maximum output power of 315 mW and pulse repetition frequency of 132.25 MHz. To the best of our knowledge, this the first report of a Tm,Ho co-doped crystalline laser that has been passively mode locked in the 2 μm spectral region. It is believed that further optimization of the absorber and laser cavity parameters will lead to subpicosecond pulse generation from this efficient, broadly tunable, and laser-diode-pumped laser.

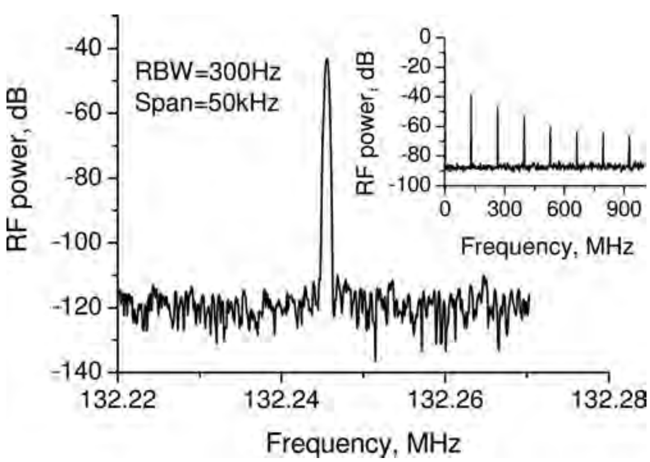

Fig. 5. RF spectral data for the mode-locked Tm,Ho:KYW laser at fundamental repetition rates. Inset, resolution bandwidth of 100 kHz and span of 1 GHz.

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