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Femtosecond (191 fs) $NaY(WO_4)_2$ Tm,Ho-codoped laser at 2060 nm

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We report, for the first time to our knowledge, femtosecond-pulse operation of a Tm,Ho:$NaY(WO_4)_2$ laser at around 2060 nm. Transform-limited 191 fs pulses are produced with an average output power of 82 mW at a 144 MHz pulse repetition frequency. Maximum output power of up to 155 mW is generated with a corresponding pulse duration of 258 fs. An ion-implanted InGaAsSb quantum-well-based semiconductor saturable absorber mirror is used for passive mode-locking maintenance.

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Compact and reliable femtosecond solid-state lasers emitting high-average power (≥100 mW) in the mid-IR (∼2–3 μm) spectral region are of considerable interest for applications in metrology, spectroscopy, medical diagnostics, soft x-ray generation, and efficient attainment of ultrashort pulses in the far-IR region. To date, a range of laser materials have been investigated to produce ultrashort pulses in the mid-IR region. The most prevalent being Tm^{3+} (Tm)- and Ho^{3+} (Ho)-doped fiber or crystalline gain media and Cr^{2+}-doped chalcogenide materials (Cr:ZnSe, Cr:ZnS). Cr^{2+}-doped crystals [1] are an attractive option for mid-IR ultrashort-pulse laser developments, because they can support widely tunable laser operation over the ∼2000–3300 nm range [2] and femtosecond-pulse generation [3]. However, Cr^{2+}-based sources require excitation in the 1500–2000 nm spectral region where high-power diode lasers (DLs) are not well developed; therefore, a cascade of lasers, such as DL-pumped Tm^{3+}- or Er^{3+}-doped fiber or crystalline lasers are predominantly used for optical pumping.

Tm-doped media are more advantageous in that respect, as they can be pumped efficiently by ∼800 nm-emitting low-cost and high-power AlGaAs DLs. Additionally, Tm-based lasers are characterized by a large continuous tuning spectral range of ∼1800–2000 nm compared to other trivalent lanthanide ions. The generation of ultrashort pulses in the 2 μm spectral band has been dominated so far by passively mode-locked Tm-doped fiber lasers. Indeed, in an early work Nelson *et al.* demonstrated 360 fs pulses [4] using the nonlinear polarization evolution (NPE) mode-locking technique, while 190 fs pulses [5] were produced by a Tm-fiber laser that was mode locked passively using a semiconductor saturable absorber mirror (SESAM). In both cases, average output powers did not exceed a few milliwatts. Recently, somewhat higher powers have been obtained from mode-locked 2 μm fiber lasers through the deployment of carbon nanotubes saturable absorbers [6,7], where pulses as short as 750 fs were produced [7]. Moreover, using the NPE approach, 1.2 ps pulses were obtained at 1980 nm with 178 mW average power directly from a laser cavity, including a Tm-doped fiber gain medium [8]. An alternative approach on generation of ultrashort pulses around 2 μm by using Tm-doped crystalline gain medium has been undertaken very recently, resulting in generation of picosecond pulses (∼10 ps) from Tm:$KLu(WO_4)_2$ laser at average power in excess of 200 mW [9].

By codoping Tm with Ho, efficient lasers can be configured to provide emission in a slightly longer wavelength range (∼2000–2150 nm) where weaker water absorption bands occur, thereby enhancing the prospects for stable mode locking. It is well known that OH-containing liquids are prone to bleaching effects on nanosecond time scales [10] that could initiate undesirable Q-switching instabilities in a solid-state laser system and prevent broadband mode locking. Recently, using a Tm–Ho codoped $KY(WO_4)_2$ gain medium, we demonstrated the generation of 570 fs pulses in a soliton mode-locking regime at 2055 nm, with an average output power of 130 mW [11]. However, the sharpness of the optical absorption and emission bands of Ho^{3+} ($4f^{10}$ electronic configuration), as in most trivalent lanthanides with $4f^N$ ($N < 11$) electronic configurations, places limits on the pulse durations that can be attained. Such a problem can be partially resolved by using inhomogeneously broadened single crystals as the gain media. In particular, rare-earth-doped tetragonal ($I\bar{4}$ space group) double tungstates with the nominal formula $NaT(WO_4)_2$ (NaTW), where Na and T = Y, La-Lu are monovalent and trivalent cations, respectively, are characterized by large optical bandwidths that arise from the quasi-random occupancy of two nonequivalent lattice sites ($2b$ and $2d$) by Na and T cations [12]. These crystals have been studied comprehensively in recent years when doped with Yb^{3+} or Tm^{3+} ions [13].

Here we report a cw passively mode-locked Tm–Ho codoped NaYW laser at 2060 nm by using ion-implanted InGaAsSb quantum-well SESAM. Because of the exploitation of large optical bandwidths of Ho^{3+} in locally

disordered NaYW crystal [14] (comparable to those in amorphous media) and an optimally designed SESAM structure, we have demonstrated the generation of transform-limited 191 fs pulses with an average output power of 82 mW.

The laser is shown schematically in Fig. 1. The Tm (4.68 at.%), Ho (0.29 at.%) codoped NaYW gain element was 3.8 mm in length and oriented in the cavity for π polarization with Brewster-angle incidence. To support a long-term stable laser operation, the gain element was mounted onto a copper heat sink that was maintained at 20 °C using a thermoelectric cooler. A highly asymmetric, astigmatically compensated Z-fold resonator was configured with two folding mirrors M_1 and M_2 having the radii of curvature of −75 mm and −100 mm, respectively, an output coupler (OC) with 1% transmission around 2 μm, and an SESAM. The choice of an asymmetric cavity design allows the cavity beam waist on the SESAM to be varied easily over a relatively wide range (~20–400 μm in radius) by adjusting the crystal and the mirror M_2 separation and length of the short arm of the resonator. The laser beam mode radii inside the gain crystal were calculated to be 28 μm × 56 μm. A Ti:sapphire laser producing 1.1 W of output power at 795 nm was used as the pump source and its beam (π polarized) was focused into the gain medium via a 63 mm focal length lens to a spot radius of 29 μm ($1/e^2$ intensity) measured in air at the location of the input facet of the gain crystal. The SESAM structure used for the initiation and stabilization of passive mode locking was similar to that described in [11], with the difference that ion implantation with 2 MeV N^+ ions at a dosage level of 2×10^{11} ions/cm^2 was applied to reduce the absorber recovery time. This ion-implanted SESAM was characterized to have about 1% of insertion losses compared to 0.8% for the as-grown structure at 2060 nm. Two IR-grade fused silica prisms with a tip-to-tip separation of 7 cm were used for the intracavity group-velocity dispersion (GVD) control.

The maximum average output power during the single-pulse mode-locked operation reached 155 mW (higher-power regime) from 900 mW of absorbed pump power (Fig. 2, circles). The rf spectrum of the mode-locked Tm,Ho:NaYW laser, which was measured at a resolution of 300 Hz and a 50 kHz span, displayed the fundamental beat note at 144.2 MHz with the extinction ratio of 66 dB above the noise level. To support this single-pulse mode-locking regime, the laser cavity beam size on the SESAM was maintained to be 135 μm in radius and the intracavity GVD was adjusted to −2489 fs^2 per round trip. This included −709.8 fs^2 from the gain medium (−93.4 fs^2/mm at 2055 nm) and the rest of the amount of −1779.2 fs^2 was contributed mainly by the beam dispersion in the prism glass material (−114 fs^2/mm at 2055 nm). A larger amount of the negative dispersion (it was varied by insertion of more prism glass material) resulted in longer pulse durations at a given intracavity power, whereas less GVD led to the initiation of a multi-pulse mode locking at maximum pulse energies. The pulse durations decreased inversely proportionally to the intracavity pulse energy (E_p) from 588 fs at the mode-locking threshold (66 mW of output power, 72.6 μJ/cm^2 of intracavity fluence on the SESAM) to 258 fs at a maximum output power of 155 mW, as the soliton mode-locking theory predicts (Fig. 3, circles) [15,16]. The corresponding optical spectrum for 258 fs pulses had an FWHM of 17.6 nm at the center wavelength of 2057.3 nm, which implies a time-bandwidth product of 0.32 (Fig. 4). It should be noted that the laser operated in a Q-switched mode-locking regime when the intracavity power was below the mode-locking threshold. Another

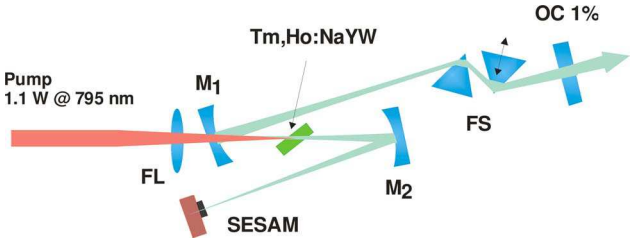

Fig. 1. (Color online) Experimental setup of the Tm,Ho:NaYW mode-locked laser: FL, focusing lens (f = 63 mm); M_1 and M_2, plano–concave high-reflective mirrors (r_1 = −75 mm, r_2 = −100 mm); OC, output coupler (T = 1% at 2000 nm); FS, pair of fused silica prisms.

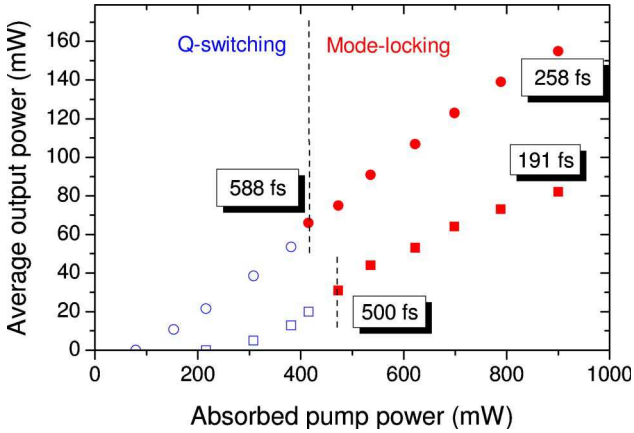

Fig. 2. (Color online) Input–output characteristics of the mode-locked Tm,Ho:NaYW laser. Two different operation regimes, shorter-pulse and higher-power, are indicated by squares and circles, respectively. Q-switching and mode-locking regimes are represented by open and closed symbols, respectively.

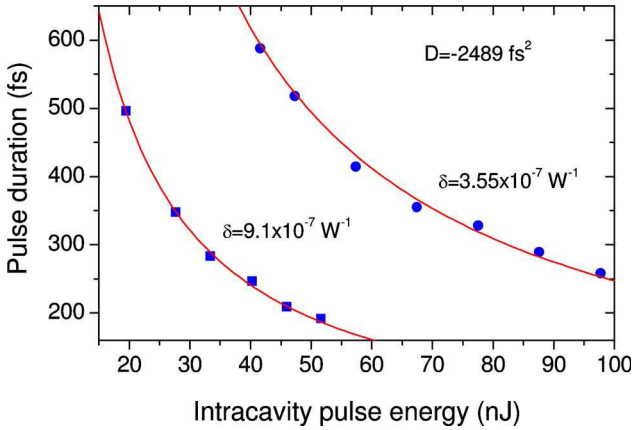

Fig. 3. (Color online) Dependence of pulse duration on the intracavity pulse energy for the two mode-locking regimes. The red curves are fits to $1/E_p$. δ is the SPM coefficient [15,16].

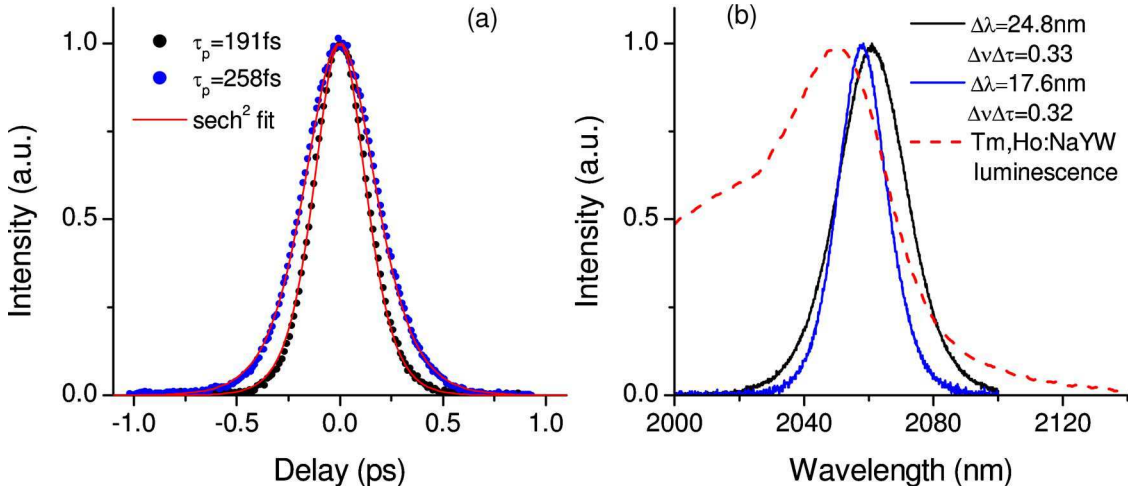

Fig. 4. (Color online) Output mode-locking parameters of the Tm,Ho:NaYW laser. (a) Intensity autocorrelation of 191 fs and 258 fs pulses and (b) corresponding optical spectra. The dashed red curve in (b) is the luminescence spectrum of Tm,Ho:NaYW at around 2060 nm.

femtosecond regime with shorter pulse durations (shorter-pulse regime) but with lower average output powers (Figs. 2 and 3, squares) was found for the same cavity configuration but following minor adjustment of the separation of mirror M_2 and the gain medium. Near transform-limited pulses as short as 191 fs [Fig. 4(a)] with a corresponding spectral bandwidth of 24.8 nm [Fig. 4(b)] at a center wavelength of 2060 nm were generated during this experimental approach at a maximum output power of 82 mW. We attribute this shorter-pulse generation regime to a more pronounced self-phase modulation (SPM) inside the gain medium resulting from tighter mode focusing conditions. However, the reduced cavity mode size inside the laser crystal results in a poorer pump-to-laser mode overlap, and this explains the observed lower laser efficiency and thermally induced rollover of output power feature.

In conclusion, by exploiting the large optical bandwidths of Ho^{3+} in a locally disordered $NaY(WO_4)_2$ crystal and an optimally designed InGaAsSb-based SESAM, considerable progress in the development of ultrashort-pulse Tm–Ho lasers operating around the 2 μm spectral region has been achieved. Applying a passive mode-locking technique, pulses as short as 191 fs were generated with an average output power of 2 orders of magnitude larger than those obtained with SESAM technology from the Tm-fiber laser having similar pulse durations [5]. The presently generated pulses are also shorter, at similar average output power level, than those obtained by out-of-cavity pulse compression of NPE mode-locked Tm-fiber laser output [8]. Moreover, ~6 times lower absorbed pump power was required in the present case. It can be seen from the luminescence and mode-locked spectra of Tm,Ho:NaYW at around 2050 nm [Fig. 4(b)] that further refinement could lead to the pulse shortening to ~100 fs.

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