Diode-pumped passively mode-locked $Er,Yb:YAl_3(BO_3)_4$ laser at 1.5–1.6 μm

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We report the first demonstration to our knowledge of passive mode locking in a diode-pumped Er^{3+} and Yb^{3+} codoped $YAl_3(BO_3)_4$ laser operating in the 1.5–1.6 μm spectral region. Low-loss GaInNAs quantum-well semiconductor saturable absorber mirrors are used for the initiation and stabilization of the ultrashort-pulse generation. Pulses as short as 4.8 ps were generated at 1530 nm with an average output power up to 280 mW for 2 W of absorbed pump power produced by a high-brightness tapered 980 nm laser diode. Passive mode locking has also been demonstrated around 1555 nm with typical average powers of around 100 mW and pulse durations of 5.1 ps. © 2007 Optical Society of America

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Solid-state laser sources operating in the 1.5 μm spectral region are in demand for a range of applications that exploit their characteristics for eye safety and for transparency in the atmosphere and in silica-based optical waveguides and fibers. Specifically, when these lasers are passively mode locked to produce ultrashort pulses with high repetition rates they are especially useful as pulse generators for high-bit-rate optical networks. The use of ultrashort pulse lasers based on ion-doped crystalline or glassy gain media operating in the 1.5–1.6 μm wavelength region is the simplest approach for development of laser systems for telecom applications owing to their potential to deliver high-quality mode-locked pulses at high average power, repetition rate, and mode-locking stability. However, the choice of such gain materials is rather limited. Only Er,Yb codoped solid-state hosts can be considered attractive gain media for compact and reliable 1.5–1.6 μm laser sources because of the efficient pumping around 980 nm by readily available InGaAs laser diodes. For low-threshold and efficient operation of Er,Yb codoped lasers two primary conditions should be satisfied. First, the $^4I_{11/2}$ Er^{3+} level, where energy transfer from the excited $^2F_{5/2}$ Yb^{3+} level occurs, should possess a short lifetime. Otherwise energy transfer back to ytterbium ions will take place, and this together with upconversion processes in the $Er^{3+}-Yb^{3+}$ system will significantly depopulate the upper laser level and reduce the laser efficiency at 1.5 μm. The second condition relates to the requirement for a high quantum yield in the luminescence around 1.5 μm. These requirements are well satisfied in Er,Yb codoped glass-based gain media; however, because of the low thermal conductivity of the glass host, the average output powers from Er,Yb:glass lasers generally do not exceed a few hundred milliwatts during continuous-wave (cw) operation and is usually less than the 100 mW level when the laser is passively mode locked [1,2]. This severely limits the ability of such lasers to operate at high pulse repetition frequencies without Q-switching instabilities [3]. Specific saturable absorber parameters such as ultralow-saturation fluence and small modulation depth are required under these conditions of modest intracavity power to ensure that stable mode-locked operation is maintained [4]. In this context, Er,Yb codoped gain media based on crystalline hosts that are characterized by better thermal properties than those for glass represent superior options for incorporation into higher power 1.5 μm ultrashort-pulse lasers. It has been shown that Er,Yb codoped crystals incorporating BO_3 groups are excellent candidates for efficient lasing in 1.5–1.6 μm range [5,6]. Generally, such media are characterized by a high phonon cutoff energy ($\sim 1400\ \mathrm{cm}^{-1}$) that facilitates a high multiphonon nonradiative decay probability from the $^4I_{11/2}$ level to the $^4I_{13/2}$ level of Er^{3+}, and this in turn reduces the losses due to upconversion and excited-state absorption in Er^{3+} and $Er^{3+}-Yb^{3+}$ systems. Very recently, a new candidate [$Er^{3+},Yb^{3+}:YAl_3(BO_3)_4$ (Er,Yb:YAB)] from this family has been introduced [7,8], and with this crystal excellent laser performance has been demonstrated with slope efficiencies as high as 35% and cw powers up to 1 W at 1555 nm [9]. Previously, the YAB crystalline matrix was used successfully for doping with some rare-earth ions like Nd^{3+} [10] and Yb^{3+} [11], and these laser materials have compatibility with high-power and compact near-IR laser sources because of their relatively high thermal conductivity of $4.7\ \mathrm{W\,m^{-1}\,K^{-1}}$ and good chemical stability, mechanical strength, and optical quality. Moreover, YAB possesses high second-order nonlinearity that can be exploited for the develop-

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ment of self-frequency-doubled solid-state laser systems that operate in the near-IR and visible ranges [12,13].

Here we report, for the first time to our knowledge, a passively mode-locked Er,Yb:YAB laser that has generated picosecond pulses in the 1.5–1.6 μm spectral region with average powers that reach 280 mW. We believe that this is the first report of a passively mode-locked Er,Yb codoped laser based on a crystalline gain medium.

To make the assessments reported here, a cw version of the Er,Yb:YAB laser, pumped by a tapered single-mode 980 nm laser diode, was first constructed and evaluated (Fig. 1). This pump laser diode produced up to 3 W of average power and had a beam quality factor M^2 of 3. A combination of aspherical ($f=15$ mm), cylindrical ($f_1=-7.7$ mm, $f_2=100$ mm), and focusing lenses ($f=80$ mm) was used to collect, reshape, and focus the pump beam into the gain medium, and the pump beam spot radius was measured to be 31 μm ($1/e^2$ intensity). The plane–plane a-cut Er(1 at. %), Yb(11 at. %):YAB crystal [8] was 1.76 mm long, antireflection coated for both pump and lasing bands, and characterized by a low-signal absorption coefficient of 12 cm^{-1} at around 980 nm (σ polarization). An asymmetric Z-fold cavity was configured to accommodate mode radii inside the crystal and on the saturable absorber of 31 μm and in the range of 70–140 μm, respectively. Laser thresholds for cw operation of the Er,Yb:YAB laser were in the range of 30–270 mW of absorbed pump power when output couplers of 0.5%–5% transmission were used. The laser output consisted of a group of longitudinal modes randomly distributed between σ and π polarizations and centered at 1602 nm when 0.5%, 1%, and 2% output couplers were used. For 5% output coupling the laser emission was σ polarized at 1531 nm, and a maximum output power of 295 mW was achieved with a slope efficiency of 16%. The Er,Yb:YAB crystal absorbed around 67% of σ-polarized pump radiation (2 W of average pump power) during lasing. With a 1% output coupler and an intracavity fused silica prism, the cw laser output could be tuned discretely in the range of 1530–1600 nm with the most pronounced peaks at 1531, 1555, and 1602 nm, with corresponding powers of 242 mW, 184 mW, and 208 mW, respectively (Fig. 2, right-hand axis). The laser crystal was maintained at a temperature of 18 °C, and no power instabilities related to thermal effects inside Er,Yb:YAB media were observed during the cw operation. It should be noted that concentrations of Er^{3+} and Yb^{3+} in YAB crystal have not yet been optimized, and further improvement of cw laser performance should be achievable.

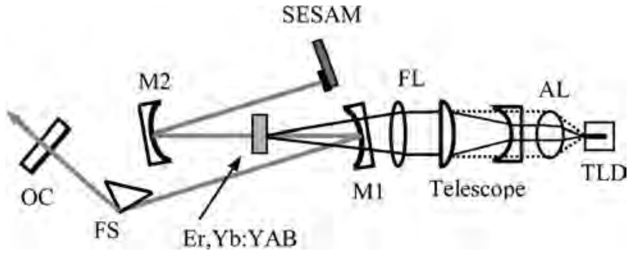

Fig. 1. Schematic of passively mode-locked Er,Yb:YAB laser. TLD, tapered laser diode ($P_{\text{out}}=3$ W at 980 nm); AL, aspherical lens ($f=15$ mm); Telescope, two cylindrical lenses ($f_1=-7.7$ mm, $f_2=100$ mm); FL, focusing lens ($f=80$ mm); M1 and M2, folding mirrors ($r_1=-100$ mm, $r_2=-75$ mm); FS, fused silica prism; OC, output coupler ($T=0.5\%, 1\%, 2\%, 5\%$).

The semiconductor saturable absorber mirrors (SESAMs) [14] used for the initiation and stabilization of passive mode locking in the Er,Yb:YAB laser incorporated a distributed Bragg reflector structure having a high reflectivity at 1480–1650 nm and InGaAsN quantum wells (QWs) layers to act as an absorber [15]. The distributed Bragg reflector structure comprised 25 pairs of 133 nm thick ($\lambda/4$) $\text{Al}_{0.95}\text{Ga}_{0.05}\text{As}$ and 113 nm thick ($\lambda/4$) GaAs layers. The absorber region was a 6 nm thick InGaAsN quantum well within a one-monolayer-thick InAs layer inserted at the center and confined by $\text{GaAs}_{1-z}\text{N}_z/\text{In}_x\text{Ga}_{1-x}\text{As}_{1-y}\text{N}_y$ short-period barriers. The contents of indium and nitrogen in the absorber region were chosen to be $z\sim4\%$, $y\sim2.4\%$, and $x\sim36\%$ to achieve the photoluminescence emission–absorption band in the 1.49–1.6 μm spectral range (FWHM). Two different types of SESAM structure that incorporated either two or six quantum-well regions have been used for the assessments reported here. Specifically, the two-quantum-well SESAM was designed to have an absorption peak at 1590 nm and an absorption maximum of 3%, whereas the six-quantum-well device had a peak at 1500 nm, where the absorption was measured to be 8% (Fig. 2, left-hand axis).

By incorporating the SESAM having a peak of absorption around 1500 nm, stable mode locking of the Er,Yb:YAB laser was readily achieved around 1531 nm (5% output coupler), where the pulse durations were 3.8 ps (Fig. 3) and the average output power was 280 mW. The corresponding spectral width of 0.66 nm implied a duration–bandwidth product of 0.32 (Fig. 3, inset). A negligible difference between the output powers in cw and mode-locked regimes in the Er,Yb:YAB laser, 295 mW and 280 mW,

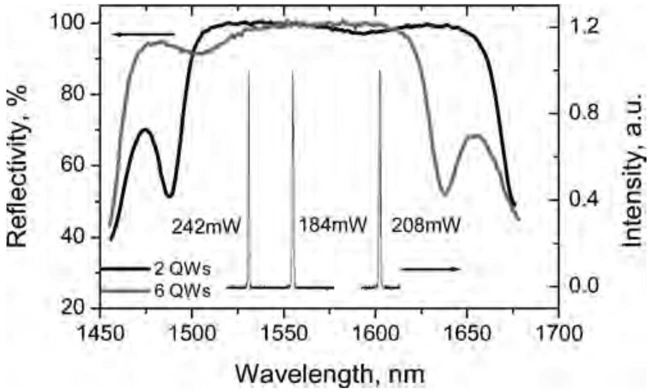

Fig. 2. Reflectivity curves of InGaAsN SESAMs having two- (dark curve) and six- (gray curve) quantum-well layers (left axis) and tunability range of cw Er,Yb:YAB laser (right axis).

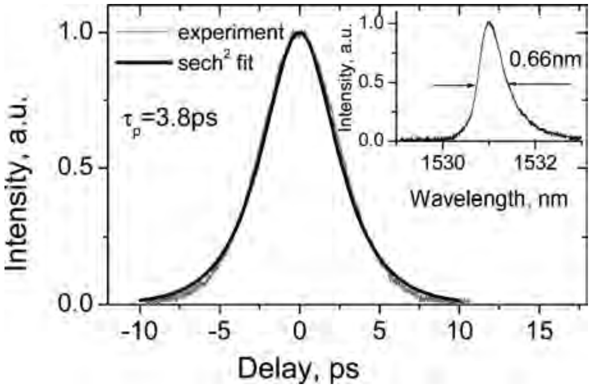

Fig. 3. Intensity autocorrelation trace of the mode-locked pulse. Inset, corresponding optical spectrum (duration–bandwidth product 0.32).

respectively, indicated that nonsaturable losses in the GaInNAs SESAM element were very small. The microwave spectrum shows a clean peak at a repetition rate of 166.57 MHz with no side peaks, thus implying the absence of Q-switching instabilities (Fig. 4), and the wide-span measurements (Fig. 4, inset) confirm single-pulse operation. Stable mode locking was observed when average output powers exceeded 150 mW (1.36 W of absorbed pump power), which corresponded to an intracavity fluence on the SESAM of 117 μJ/cm^2, whereas a Q-switched mode-locking regime arose at fluences on the saturable absorber in the range of 117–80 μJ/cm^2 (150–100 mW of average output power, 1.36–1 W of absorbed pump power). By using the SESAM with an absorption peak around 1.6 μm, stable mode locking was achieved at 1550 nm with an average output power of 103 mW for an output coupling of 1%; 5.1 ps pulses were generated with a corresponding spectral bandwidth of 0.5 nm. Additionally, passive mode locking has been demonstrated at around 1.6 μm, but this was accompanied by strong Q-switching instabilities regardless of the intracavity fluence on the SESAM. This can be explained by the nonoptimized saturable absorber parameters such as an excessive modulation depth, which was estimated to be 3% at 1600 nm for the two-quantum-well SESAM.

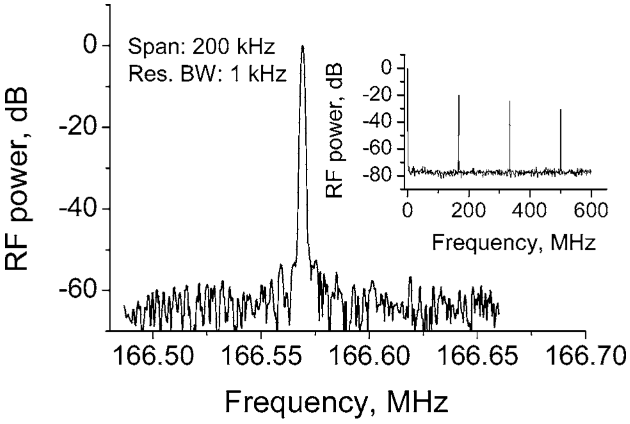

Fig. 4. RF spectrum at fundamental repetition rates. Inset, resolution bandwidth (Res. BW) 100 kHz and span 600 MHz.

In conclusion, efficient passive mode locking in a diode-pumped Er,Yb:YAB laser has been demonstrated by using low-loss GaInNAs-based SESAMs. Pulses having durations of 3.2 and 5.1 ps were produced at 1530 and 1550 nm, respectively, with corresponding average powers of 280 and 103 mW. We believe that this is the first Er, Yb ultrashort-pulse laser based on a crystalline medium that has been reported to date, and we believe that it ushers in a range of new opportunities for the development of high-power and high-repetition-rate ultrashort-pulse lasers operating in the 1.5–1.6 μm range.

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