Passively modelocked diode-pumped erbium-ytterbium glass laser using a semiconductor saturable absorber mirror

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A diode-pumped bulk Er^{3+}:Yb^{3+}:glass laser has been passively CW modelocked for the first time. Reliable, self-starting passive modelocking using semiconductor saturable absorber mirrors (SESAMs) is demonstrated, with pulses as short as 2.5ps being obtained with an average output power of 68mW at the telecommunications wavelength of ~1.5μm.

There has been growing interest in compact lasers producing picosecond pulses at the telecommunications wavelength around 1.5μm. Many applications require a clean train of pulses in the picosecond regime with pulse repetition rates not necessarily in the multi-gigahertz regime. Examples are measurements of the time response of optical switches and detectors, or material investigations for semiconductor optical amplifiers in all-optical switches.

Currently mainly Cr^{4+}:YAG and Er^{3}+:Yb^{3+}:glass are used as gain material for pulsed bulk lasers around 1.5μm. Cr^{4+}:YAG has been passively modelocked by Kerr lens modelocking (KLM) [4] or by semiconductor saturable absorber mirrors [2]. However, this laser requires a high-brightness multi-Watt pump because of its weak absorption and high laser threshold. Er^{3}+:Yb^{3+}:glass is a quasi-three-level gain material which can easily be diode-pumped, because co-doping with ytterbium facilitates an efficient pump process around 980nm without increasing the reabsorption losses [3]. Actively modelocked operation of a bulk Er^{3+}:Yb^{3+}:glass laser has been demonstrated [4] producing 9.6ps at 3mW output power.

Passively modelocked erbium-doped fiber lasers have been shown to produce sub-picosecond pulses with nanojoule pulse energies using different approaches [5, 6]. However, the pulses of the side- and cladding-pumped erbium laser [6] show large wings, which contain a significant amount of the energy. The additive-pulse-modelocking approach using the rejection port for output coupling [5] shows better pulse quality but depends on a rather sophisticated and expensive master-oscillator/power amplifier pump source. In this Letter we report the first demonstration of a passively CW modelocked diode-pumped bulk Er^{3+}:Yb^{3+}:glass laser yielding good stability and pulse quality.

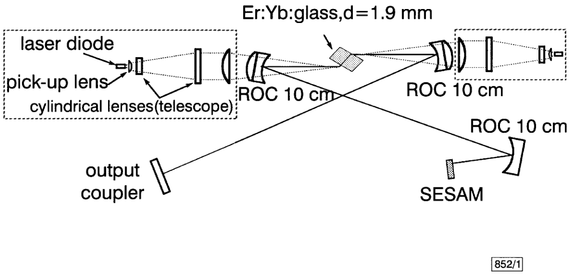

Fig. 1 *Diode-pumped Er^{3+}:Yb^{3+}:glass cavity setup*

The arm lengths of the delta cavity are 50cm and 65cm from the folding mirrors to the output coupler and the SESAM, respectively (ROC: radius of curvature; SESAM: semiconductor saturable absorber mirror)

Fig. 1 shows our laser resonator without any dispersion compensation. We used 1.9mm thick erbium and ytterbium doped Kigre QX/Er phosphate glass, doped with 7.3 × 10^{19} Er-ions/cm^3 and 1.8 × 10^{21} Yb-ion/cm^3. The thickness of the gain medium is chosen to be not significantly more than the absorption length (1.6nm), to minimise the reabsorption losses. However, pumping from both allows the use of a slightly thicker gain material. The glass was longitudinally pumped by one or two 700mW high-brightness, 30μm stripe size, broad area InGaAs/GaAs laser diodes operating at 968nm. For optimised mode-matching we chose a pump beam waist in the gain medium of 43 × 22μm radius, which sets the confocal parameter in the slow axis of the diode in the range of the absorption length of the E^{3}+:Yb^{3+}:glass. The laser beam waist inside the Er^{3+}:Yb^{3+}:glass was calculated to be 48 × 28μm, slightly larger than the pump to obtain small reabsorption losses in the wings of the beam and a clean TEM_{00} mode.

Reliable self-starting passive CW modelocking is achieved with a semiconductor saturable absorber mirror (SESAM) [7] which forms one end mirror of the laser cavity. The SESAM (Fig. 2) is a low-finesse antiresonant Fabry-Perot saturable absorber (A-FPSA) with a AlAs/GaAs bottom Bragg mirror (25 layer pairs) grown on a GaAs substrate. Four highly strained 15nm thick $In_{0.53}Ga_{0.47}As$/GaAs quantum wells were grown on the top of this mirror with molecular beam epitaxy (MBE) at low temperature (350°C). Usually, semiconductor lasers, detectors, amplifiers, and SESAMs in the 1.5μm spectral region are based on lattice-matched InGaAsP/InP quantum wells and InP substrates [8]. Strained InGaAs/GaAs quantum wells have an advantage in that they can be grown on a GaAs/AlAs Bragg mirror which has a much wider reflection bandwidth than an InGaAsP/InP mirror. Furthermore, significantly fewer layers are required for a high reflectivity due to the larger refractive index difference. The tradeoff is a poorer surface quality, due to possible cross-hatches, if large modulation and therefore many quantum wells are required. Low-temperature MBE growth can partially relieve the lattice mismatch and additionally leads to shorter absorber lifetimes by incorporating defects. Our SESAM (Fig. 2) has a measured modulation depth of 1.3%, non-saturable losses of 3.2%, a fast recovery time of 500fs due to intraband thermalisation, a slow interband recombination time of 13ps, and a saturation fluence of 70μJ/cm^2 [7].

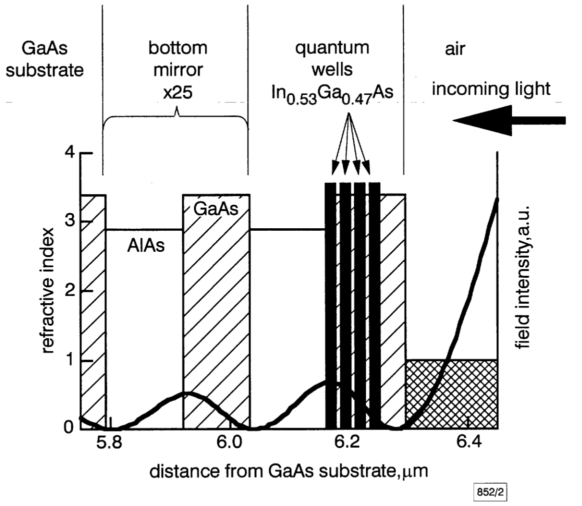

Fig. 2 *Semiconductor saturable absorber mirror (SESAM) design with highly strained InGaAs quantum wells and standing wave pattern of the optical field in the structure*

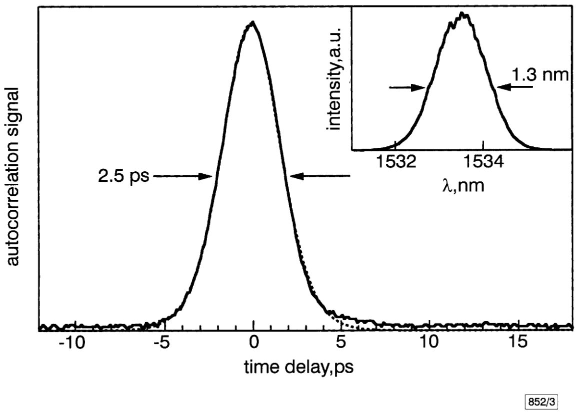

Fig. 3 *Autocorrelation trace and spectrum of shortest pulses*

········ autocorrelation of ideal 2.5ps $sech^2$ pulse
Inset: spectrum

We obtained stable CW modelocking without Q-switching instabilities even though Er^{3+}:Yb^{3+}:glass has a small emission cross-section ($\sigma_L = 8 \times 10^{21} cm^2$) and a long upper state lifetime (τ_L = 7.9ms), which strongly enhances the tendency for Q-switched modelocking [9]. We could prevent any Q-switching instabilities with an incident pulse fluence on the SESAM of about 9 times the saturation fluence and a beam radius of 34 × 30µm on the SESAM. At much higher fluences multiple pulsing was observed [10]. We obtained clean 2.5ps pulses with an average output power of 68mW at a pulse repetition rate of 114 MHz and a centre wavelength of 1534nm (Fig. 3). The bandwidth of 1.3nm corresponds to a time bandwidth product of 0.41. The total pump power was 590mW and the output coupling 3%. The highest modelocked output power that we obtained was 105mW with sub-6ps pulses using an output coupling of 10%. At pump powers > 1W we observed thermal damage of the glass. However, no active cooling was applied, and the transverse dimensions of the gain glass plate were 1 × 1cm. Therefore even higher output powers should be possible, if better thermal management is carried out. We have used different host glasses such as QE-7, and QE-20 (Kigre Inc.) but the QX/Er glass showed by far the best thermal properties.

For CW operation we replaced the curved mirror and the SESAM at one end of the cavity (Fig. 1) by a flat high reflector. We achieved output powers up to 183mW at pump powers of 500mW from each side using a 10% output coupler. By pumping with one single diode we obtained a slope efficiency of 33% and a laser oscillation threshold of 62mW absorbed pump power with the same 10% output coupler. In CW operation we were able to tune the laser between 1500 and 1568nm. Tuning was obtained by tilting one end mirror and using a single prism inside the laser resonator. In modelocked operation the laser was not tunable, as the bandgap of the absorber is located around 1540nm and tuning the laser to longer wavelengths resulted in CW rather than modelocked operation.

In conclusion, we have demonstrated the first passively modelocked diodepumped bulk Er^{3+}:Y^{3+}:glass laser. We obtained shorter pulses and significantly higher pulse energies than previously obtained with actively modelocked bulk Er^{3+}:Y^{3+}:glass lasers [4].

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References

1 SENNAROGLU, A., POLLOCK, C.R., and NATHEL, H.: ‘Continuous-wave self-modelocked operation of a femtosecond Cr^{4+}:YAG laser’, *Opt. Lett.*, 1994, **19**, pp. 390–392

2 COLLINGS, B.C., STARK, J.B., TSUDA, S., KNOX, W.H., CUNNINGHAM, J.E., JAN, W.Y., PATHAK, R., and BERGMAN, K.: ‘Saturable Bragg reflector self-starting passive modelocking of a Cr^{4+}:YAG laser pumped with a diode-pumped Nd:$YV0_4$ laser’, *Opt. Lett.*, 1996, **21**, pp. 1171–1173

3 GAPONTSEV, V.P., MATITSIN, S.M., ISINEEV, A.A., and KRAVCHENKO, V.B.: ‘Erbium glass lasers and their applications’, *Opt. Laser Technol.*, 1982, **14**, pp. 189–196

4 LAPORTA, P., LONGHI, S., MARCHESI, M., TACCHEO, S., and SVELTO, O.: ‘2.5 GHz and 5 GHz harmonic mode-locking of a diode-pumped bulk erbium-ytterbium glass laser at 1.5 microns’, *IEEE Photonics Technol. Lett.*, 1995, **7**, pp. 155–157

5 LENZ, G., TAMURA, K., HAUS, H.A., and IPPEN, E.P.: ‘All-solid-state femtosecond source at 1.55µm’, *Opt. Lett.*, 1995, **20**, pp. 1289–1291

6 HOFER, M., FERMANN, M.E., and GOLDBERG, L.: ‘High-power side-pumped passively mode-locked Er-Yb fiber laser’, *IEEE Photonics Technol. Lett.*, 1998, **10**, pp. 1247–1249

7 KELLER, U., WEINGARTEN, K.J., KÄRTNER, F.X., KOPF, D., BRAUN, B., JUNG, I.D., FLUCK, R., HÖNNINGER, C., MATUSCHEK, N., and AUS DER AU, J.: ‘Semiconductor saturable absorber mirros (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers’, *IEEE J. Sel. Topics Quantum Electron.*, 1996, **2**, pp. 435–453

8 FLUCK, R., HÄRING, R., PASCHOTTA, R., GINI, E., MELCHIOR, H., and KELLER, U.: ‘Eyesafe pulsed microchip laser using semiconductor saturable absorber mirrors’, *Appl. Phys. Lett.*, 1998, **72**, pp. 3273–3275

9 HÖNNINGER, C., PASCHOTTA, R., MORIER-GENOUD, F., MOSER, M., and KELLER, U.: ‘Q-switching stability limits of continuous-wave passive mode locking’, *J. Opt. Soc. Amer. B*, 1999, **16**, pp. 46–56

10 KÄRTNER, F.X., AUS DE R AU, J., and KELLER, U.: ‘Modelocking with slow and fast saturable absorbers - What’s the difference?’, *IEEE J. Sel. Topics Quantum Electron.*, 1998, **4**, pp. 159–168