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Efficient, low-noise, SESAM-based femtosecond Cr^{3+}:$LiSrAlF_6$ laser

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Abstract

We report what we believe to be the first demonstration of a SESAM (semiconductor saturable absorber mirror)-based femtosecond Cr^{3+}:$LiSrAlF_6$ laser pumped by narrow-stripe AlGaInP laser diodes that have diffraction-limited output beams. A highly asymmetric, four-mirror laser cavity design is described for which 57 fs duration pulses at an average output power of 6.5 mW are obtained for only 72 mW of incident pump power. Pump powers of this order were maintained for over 14 h using just six 1.5 V AA batteries as the electrical power source. We have shown that mode-locking can be sustained for incident pump powers as low as 21.5 mW. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

In the research that is directed towards the development of compact all-solid-state femtosecond lasers, the impact of combining AlGaInP laser diodes with colquiriite gain media such as Cr:LiSAF has been very significant. It has led to the demonstration of extremely efficient sources of femtosecond pulses and although there now exist diode-pumped-solid-state (DPSS) lasers for pumping Ti:sapphire, directly diode-pumped femtosecond lasers have obvious advantages: not least of cost. Since the first report of such a system [1] there have been notable developments in mode-locked Cr:LiSAF lasers that incorporate semiconductor saturable absorbing mirrors (SESAM) [2], SESAMs that compensate for positive dispersion [3] and Kerr-lens mode-locked (KLM) versions [4]. The main thrust of these recent enhancements has been directed towards increasing the average output powers of the lasers such that up to 500 mW has already been reported [5]. There are, however, applications that do not require average output powers of this scale but for which stable and low-noise pulse sequences with average powers of the order of a few milliwatts would suffice. This low-power configuration has the additional advantages of simplicity and increased overall efficiency.

In this Letter we report a femtosecond Cr^{3+}:$LiSrAlF_6$ laser based on a highly asymmetric four-mirror geometry where the mode-locking is initiated and sustained using a SESAM incorporating a GaAs quantum well [3,5]. This cavity retains the low pump power requirements of a previously reported three-mirror KLM laser [6] allowing the use of diffraction-limited narrow stripe AlGaInP laser diodes (stripe widths 4–5 μm) to pump the laser. The inclusion of the SESAM permitted the use of a 1.5% output coupler in the cavity and an order of magnitude greater average output power to be obtained. This new

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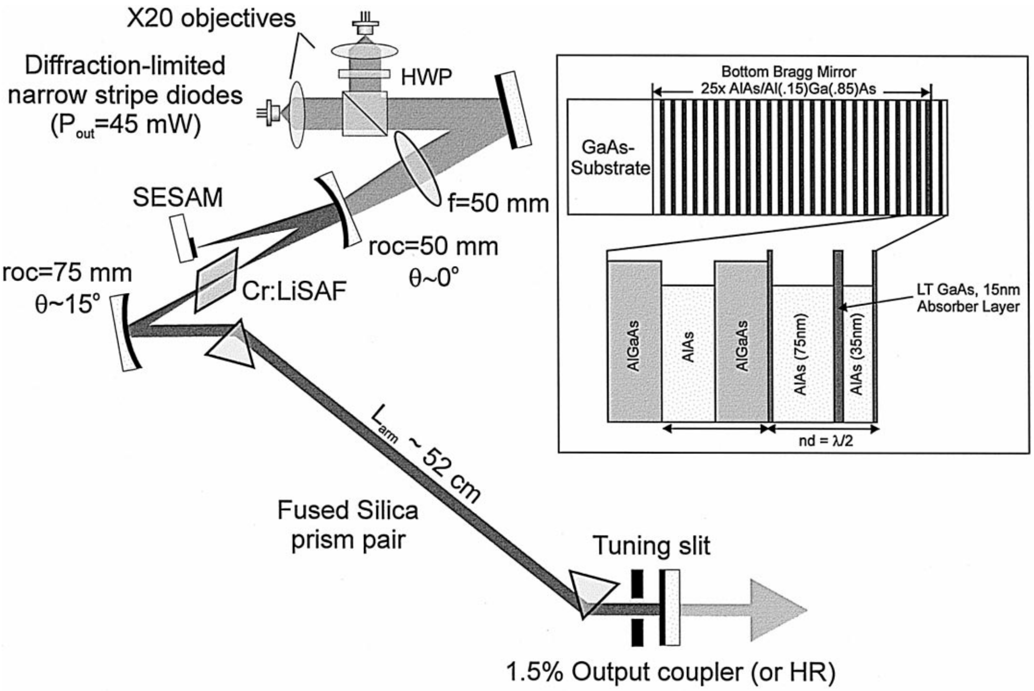


Fig. 1. Schematic of the low-threshold SESAM-mode-locked Cr:LiSAF laser cavity pumped by diffraction-limited Philips 50 mW laser diodes. (Inset: schematic of AlAs/GaAlAs SESAM.)

resonator configuration also provided an entirely self-starting femtosecond pulse operation.

2. Experiment

Fig. 1 shows a schematic of the complete cavity and pumping geometry used for the femtosecond Cr:LiSAF laser. A highly asymmetric four-mirror Z-cavity design is used in which the large angle ($\sim 30°$) between the long cavity arm and the folding section compensates entirely for the astigmatism introduced by the Brewster-angle cut gain medium (7 mm crystal of Cr^{3+}:$LiSrAlF_6$ with 1.5% Cr^{3+} doping). Provided that the angle between the folding section and the short cavity arm is small (close to zero), the pump and cavity modes may be tightly focused and made to coincide on the pumped crystal facet, thereby ensuring a low cw threshold. The highly asymmetric cavity design allows the cavity beam waist on the SESAM to be varied easily by adjusting the length of the short cavity arm (see Fig. 2). This enables the saturation of the SESAM to be optimised for variable intracavity powers. Initially the intracavity field was focused to a 22 μm spot radius on the SESAM by setting the short arm length to 54 mm.

The two curved folding mirrors had radii of curvature of 50 and 75 mm for the short and long cavity arms, respectively, and had high-reflectivity (HR) coatings centred around 850 nm (LaserOptik GmbH, $T = 0.05\%$). The plane end-mirror was either a HR coated mirror or a 1.5% transmitting output coupler. A slit placed in front of this end-mirror allowed the laser wavelength to be tuned to the bandgap of the SESAM around 860 nm. The total cavity length was approximately 1 m, giving a pulse repetition frequency of ~ 150 MHz. Intracavity dispersion compensation was provided by a pair of low insertion loss Infrasil fused-silica prisms separated by 51 cm. Fused silica was chosen initially to minimise the intracavity third-order dispersion originating from the prism pair.

The SESAM was a broadband low-finesse, antiresonant Fabry-Perot saturable absorber (A-FPSA) which has been described elsewhere [5,7]. The structure of the SESAM is shown in the inset of Fig. 1 and its characteristics are described comprehensively in Ref. [5]. It suffices to say

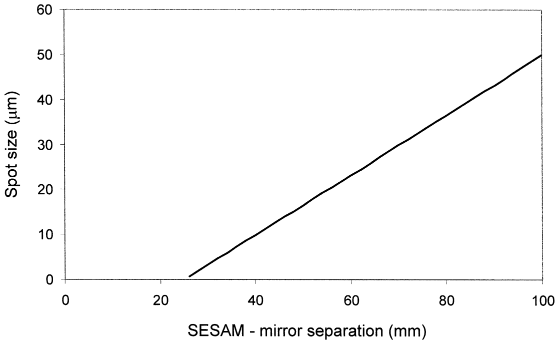


Fig. 2. Variation of intracavity focus on the SESAM with varying short cavity arm length.

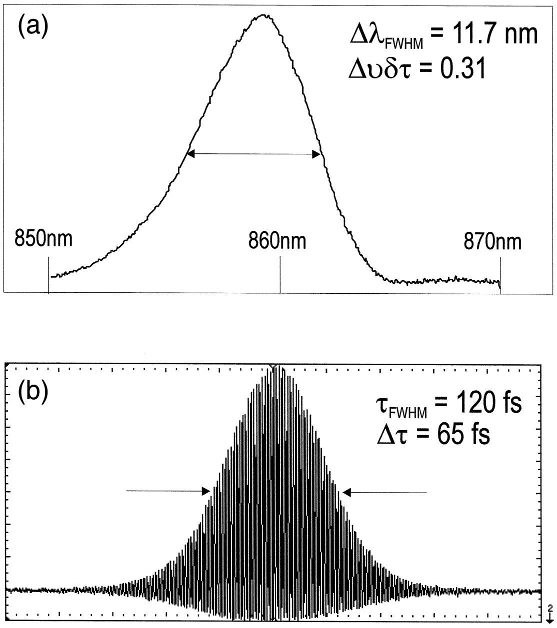


Fig. 3. Characterisation of 65 fs pulses obtained at a pump power of 72 mW (two Philips CQL 806/50 diodes): (a) interferometric autocorrelation and (b) corresponding spectrum.

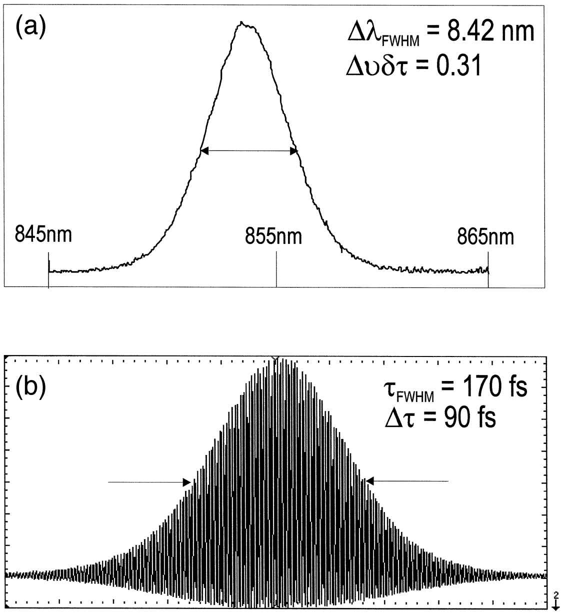


Fig. 5. Characterisation of 90 fs pulses obtained at a pump power level of 80 mW and an output coupling of 1.5%: (a) interferometric autocorrelation and (b) corresponding spectrum.

here that this low-finesse Fabry-Perot is defined by the Fresnel reflectivity of the semiconductor–air interface at the top of the device ($R \approx 31\%$) and the MOCVD grown AlAs/AlGaAs Bragg mirror centred at 850 nm ($R > 99.5\%$). The SESAM was designed to give a relatively flat low-intensity (unsaturated) reflectivity of $98.5 \pm 0.7\%$ across a wavelength range of 50 nm. A 15 nm thick absorber quantum well is positioned within a half-wavelength, transparent AlAs spacer layer that satisfied the antiresonance condition of the F–P structure. The low-tem-

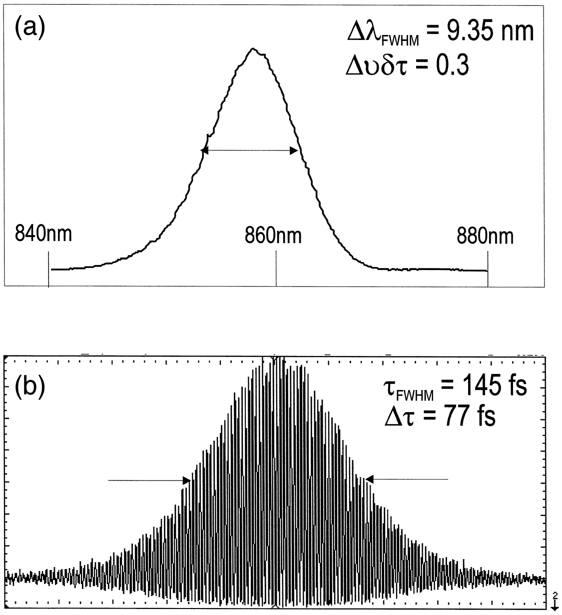


Fig. 4. Characterisation of 77 fs pulses obtained at a pump power of 35 mW (one Philips CQL 806/50 diode): (a) interferometric autocorrelation and (b) corresponding spectrum.

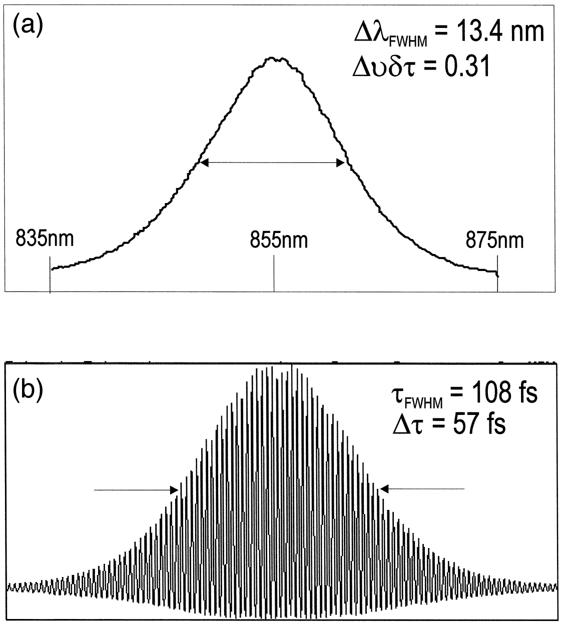


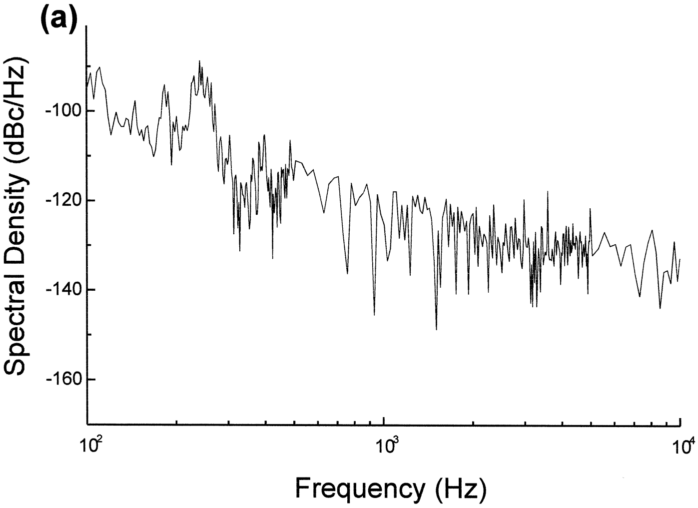
Fig. 6. Characterisation of 57 fs pulses obtained at a pump power level of 72 mW and an output coupling of 1.5%: (a) interferometric autocorrelation and (b) corresponding spectrum.

perature (400°C) MBE-grown GaAs quantum well had a bandgap that corresponded to an absorption centred at a wavelength of 860 nm. The SESAM used had a saturation fluence of 160 $\mu J/cm^2$ at 830 nm and was not significantly different at the preferred operating wavelength based around 860 nm. Its associated maximum reflectivity when saturated was 99.5% giving a modulation depth of ~ 1.4%.

The two pump laser diodes were type-CQL 806/50 prototype narrow-stripe AlGaInP devices supplied by Philips Optoelectronics Research [8]. The diodes were specified to produce up to 50 mW at 680 nm from the diode facet in a 3:1 elliptical beam when collimated. The use of such diffraction-limited sources allows simple coupling optics to be employed and a more efficient pump/cavity mode overlap to be obtained. No reshaping of the elliptical mode was employed. The diode emissions were oriented parallel and collimated using standard ×20 microscope objective lenses. The beams were then combined in a Glan–Thompson polarising cube using a half-wave plate to rotate the polarisation of one of the diodes. This pump light was subsequently focused into the gain medium using a 5 cm focal length spherical lens.

3. Results

The cw threshold of the laser was measured to be 20.4 mW with an HR end-mirror when pumped with a single diode having its *E*-field polarised parallel to the crystal *c*-axis (p-polarised). Absorption of Cr:LiSAF for p-polarised light is approximately twice that for s-polarised light at 670–680 nm. Tuning the laser for mode-locked operation while maintaining optimum GVD conditions, yielded a stable self-starting train of transform-limited 65 fs pulses from the HR end-mirror (see Fig. 3). An average output power of 920 μW was obtained from each of the cavity HR-mirrors for an incident pump power of 72 mW. With the cavity in this configuration the laser was pumped with a single narrow-stripe pump diode (p-polarised) giving a maximum available pump power of 35 mW incident on the crystal. At this lower pump power the laser pro-



(b)

Frequency	Free-running Low-threshold Cr:LiSAF laser with SESAM	Free-running Low-threshold KLM Cr:LiSAF laser[6]	Free-running KLM Ar+-pumped Ti:Sapphire laser[10]	Actively-stabilised KLM Ar+-pumped Ti:Sapphire laser[10]
50-1000Hz	1 200 fs	2 200 fs	—	—
100-500Hz	302 fs	680 fs	3 400 fs	150 fs
500-5000Hz	73 fs	73 fs	800 fs	80 fs

Fig. 7. Phase-noise measurements on the battery-operated femtosecond Cr:LiSAF laser pumped by two laser diodes: (a) single-sideband phase-noise spectrum, (b) comparison of timing jitter with low-noise, KLM diode-pumped Cr:LiSAF and Ar$^+$-pumped Ti:sapphire lasers.

duced 77 fs pulses at an average output power of 460 μW (see Fig. 4) and mode-locked operation ceased only when the pump power was reduced below 21.5 mW. This value is close to the cw threshold of the laser and is an indication of the higher reflectivity available from the SESAM when saturated.

By replacing the mains electrical power supplies to the laser diodes by a battery pack containing six 1.5 V AA-type penlight batteries and a low drop-out voltage regulator circuit (LP2952), the diodes provided up to 80 mW of incident pump power. When the high-reflectivity plane mirror was replaced with a 1.5% output coupler, the laser exhibited a slope efficiency of 36% and produced transform-limited 90 fs pulses at an average output power of 9 mW (see Fig. 5). This performance represented an attractive overall electrical-to-optical efficiency of approximately 1%. Mode-locked laser operation could be sustained for over 14 h using these six batteries.

To further reduce pulse durations with the output coupler in place, the spot size on the SESAM was reduced to 13 μm to increase the incident energy fluence. This was achieved by reducing the SESAM folding mirror separation to 45 mm highlighting the suitability of the highly asymmetric cavity configuration for this purpose. The tuning slit was no longer necessary for mode-locked operation as a result of the increased cavity focussing and the cavity produced pulses as short as 70 fs at an output power of 6 mW for an incident pump power of 72 mW.

Using a complex matrix analysis of its multilayer structure the SESAM was found to contribute a minimal amount of group-velocity or second-order dispersion but a significant amount of positive third-order dispersion into the cavity [9]. For this reason the fused silica prisms were replaced with LaK31 prisms separated by 27 cm. This prism system provided a net negative third-order dispersion of a few hundred femtoseconds [3] that compensated for the dispersive effect of the SESAM [10]. In this configuration the laser produced 57 fs pulses at an average output power of 6.5 mW for an incident pump power of only 72 mW (see Fig. 6).

Using the methods described in Ref. [11], phase-noise measurements of the laser output were carried out. The laser beam was focused onto a BPW28 fast silicon-avalanche photodiode and the resulting signal displayed on a HP7000 microwave spectrum analyser system. The single sideband phase-noise spectrum is shown in Fig. 7a. Fig. 7b indicates the rms timing jitter for this laser as compared to a low-noise, KLM Cr:LiSAF laser pumped with narrow-stripe laser diodes [6], a free-running KLM Ti:sapphire laser [12] and an actively stabilised, cavity-referenced KLM Ti:sapphire laser which was coupled to a noise-eating system [12]. The noise figures compare favourably with these earlier system configurations, as the mode-locking mechanism was completely passive with no external noise reduction. A ‘worst case’ amplitude noise spectrum could only be recorded because the noise performance of this battery-operated laser was below the noise floor of our measurement system.

4. Conclusion

In summary, a compact, efficient, ultralow-noise femtosecond laser system that is pumped directly with narrow-stripe, diffraction-limited laser diodes has been demonstrated. Output powers as high as 9 mW and pulses as short as 57 fs have been obtained with a maximum available pump power of only 80 mW. The ability to use a small battery pack as an electrical power source in obtaining these results highlights the overall efficiency of the system. It follows that this low-threshold, self-starting type of laser cavity design could also be used in the direct diode pumping of other materials when either a limited pump power is available or a modest output power is acceptable.

Acknowledgements

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References

[1] R. Mellish, P.M.W. French, J.R. Taylor, P.J. Delfyett, L.T. Florez, Electron. Lett. 30 (1994) 223.
[2] D. Kopf, K.J. Weingarten, L.R. Brovelli, M. Kamp, U. Keller, Optics Lett. 19 (1994) 2143.
[3] D. Kopf, G. Zhang, R. Fluck, M. Moser, U. Keller, Optics Lett. 21 (1996) 486.
[4] S. Uemura, K. Miyazaki, Optics Comm. 138 (1997) 330.
[5] D. Kopf, K.J. Weingarten, G. Zhang, M. Moser, M.A. Emanuel, R.J. Beach, J.A. Skidmore, U. Keller, Appl. Phys. B. 65 (1997) 235.
[6] G.J. Valentine, J.-M. Hopkins, P. Loza-Alvarez, G.T. Kennedy, W. Sibbett, D. Burns, A. Valster, Optics Lett. 22 (1997) 1639.
[7] D. Kopf, A. Prasad, G. Zhang, M. Moser, U. Keller, Optics Lett. 22 (1997) 621.
[8] A. Valster, A.T. Meney, J.R. Downes, D.A. Faux, A.R. Adams, A.A. Brouwer, A.J. Corbijn, Sel. Topics Quantum. Electron. 3 (1997) 180.
[9] E.J.O. Williams, Ph.D. Thesis, The University of St. Andrews, Fife, UK, 1997.
[10] B.E. Lemoff, C.P.J. Barty, Optics Lett. 18 (1993) 57.
[11] D. Von der Linde, Appl. Phys. B. 39 (1986) 201.
[12] D.E. Spence, J.M. Dudley, K. Lamb, W. Sibbett, Optics Lett. 19 (1994) 481.