Gigahertz repetition-rate from directly diode-pumped femtosecond Cr:LiSAF laser

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Gigahertz repetition-rate, fundamental modelocking of a directly diode-pumped femtosecond laser is demonstrated for the first time. Transform-limited pulses of 146 fs duration are produced from a compact Cr:LiSAF laser incorporating a semiconductor saturable absorber mirror and pumped by inexpensive, narrow-stripe red laser diodes.

Introduction: The growth in demand for broad-bandwidth data communications means that innovative approaches are required to increase the capacity of present and future optical networks. Wavelength division multiplexing, the simultaneous transmission of a number of different data streams on separate wavelength channels, requires the generation of optical pulses across a broad range of wavelengths. Current approaches use a number of discrete semiconductor lasers to provide each of these wavelengths independently. One option for future sources may be to replace such individual narrowband lasers with a single source generating a large optical bandwidth. Femtosecond (fs) lasers have the potential to offer such bandwidths, with the additional advantage that, if the pulse repetition rate can be made high enough, it may be possible to perform optical time division multiplexing, allowing for even higher data rates. If such sources are to become practical, the cavity design and pumping requirements must be kept simple.

For the first time, diode-pumped solid-state lasers have been passively modelocked at multi-gigahertz pulse repetition rates using $Nd:YVO_4$ and an intracavity semiconductor saturable absorber mirror (SESAM) [1], producing picosecond pulses at 13 GHz at 1.06 µm wavelength [2]. With additional negative dispersion compensation and under Ti:sapphire pumping, an even higher pulse repetition rate of 77 GHz has been demonstrated [3]. Harmonically modelocked fibre lasers can provide femtosecond pulses at exceptionally high repetition rates, but these configurations tend to be complex and require sophisticated stabilisation electronics [4]. The ultimate solution would be to generate broad bandwidth pulses directly from a semiconductor laser. Currently, however, sub-picosecond pulses are only produced by quite complicated diode laser arrangements and, to date, only sub-picojoule pulse energies are available [5]. More recently passively modelocked optically pumped vertical cavity semiconductor lasers have produced significantly more average output power [6]. So far, these lasers have produced picosecond pulses.

In this Letter, we describe a directly diode-pumped Cr:LiSAF laser that can be fundamentally (i.e. not harmonically) modelocked at a repetition rate in excess of 1 GHz. It produces pulses of 146 fs duration and 5.4 nm bandwidth using a simple, compact and potentially robust cavity configuration.

Cavity design: To achieve robust and reliably self-starting modelocked operation, a SESAM [1] was used as the modelocking element. The main obstacle to modelocking at high-repetition rates with a SESAM is the tendency of the laser to run modelocked only under a Q-switched envelope when the intracavity pulse energy E_p drops below a certain level [7]. As eqn. 1 shows, this energy depends on the saturation fluence of, and mode areas incident on, the gain medium, $F_{sat,L}$ and A_L, respectively, and SESAM, $F_{sat,A}$ and A_A, respectively, as well as the modulation depth of the SESAM ΔR [7]. This inequality does not account for soliton-like pulse shaping effects within the laser which will ease this constraint somewhat, nonetheless the general design considerations that it reveals remain valid.

$$\frac{P_{ave}}{T \cdot f} = E_p > \sqrt{F_{sat,L} \cdot A_L \cdot F_{sat,A} \cdot A_A \cdot \Delta R} \quad (1)$$

For a given average output power P_{ave} and output coupler transmission T, increasing the repetition rate f necessarily reduces the intracavity pulse energy and hence the inequality in eqn. 1 becomes progressively more difficult to satisfy. This problem is compounded for the broadband gain materials used in directly diode-pumped femtosecond laser systems because they typically have low stimulated emission cross-sections and hence high saturation fluences.

For a given SESAM, the intracavity pulse energy must be suitably high, and the mode areas in the gain crystal and on the SESAM must be kept small. (A broadband SESAM, previously used in low threshold work, rather than a custom designed device, was used here [8]. It has a saturation fluence of ~160 µJ/cm^2, a modulation depth of ~1.4% and a non-saturable loss of ~1%.) However, the requirement for a small laser mode size in the gain crystal (~30 µm minimum beam radius in these experiments) means that efficient utilisation of high power but low brightness broad area laser diodes is impractical. For this reason, narrow stripe diode lasers with diffraction limited output beams of 50–60 mW were used. Four of these diodes were combined by the successive use of wavelength and polarisation coupling techniques to provide up to 180 mW of high spatial quality pump power (see Fig. 1). To further increase the intracavity pulse energy, a mirror with just 0.07% transmission was used as the output coupler. A simple asymmetric z-cavity design enabled the maintenance of small spot sizes both on the SESAM and in the gain crystal, while keeping the cavity length below the 150 mm required for a gigahertz pulse repetition rate (see Fig. 1). This cavity design also retains sufficient intracavity intensity to access the benefits of spectral broadening of the pulses due to self-phase modulation.

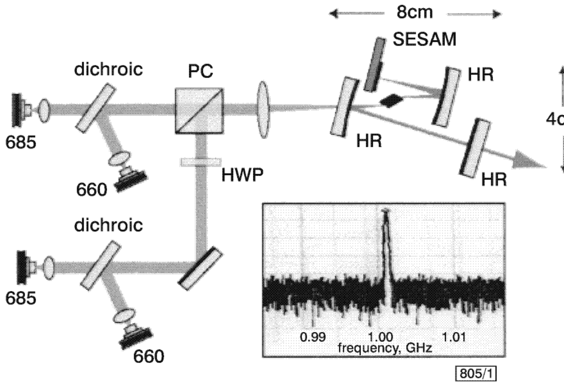

Fig. 1 *Schematic diagram of cavity design*

HR: dichoric high reflector; PC: polarisation beam splitter cube; HWP: half-wave plate
Inset: Radio-frequency spectrum of modelocked output

The method of dispersion control used has perhaps the biggest impact on the footprint and cavity length of a femtosecond laser. The prism-based systems typical of most femtosecond lasers require component separations that are incompatible with gigahertz repetition rates. Furthermore, given the limited pump powers available, the use of chirped mirror structures would result in unacceptable optical losses. In this system, a feature in the group-delay profile of the dichroic folding mirrors (supplied by QTF Inc., FL, USA) at around the lasing wavelength provided the dispersion compensation. This feature was not part of the design specifications of the mirrors. Thus, the provision of sufficient negative group delay dispersion was integrated within a mirror structure providing low losses at the laser wavelength (measured transmission < 0.03%) and high pump transmission (> 95%). By reducing the component count, this allowed for a simultaneous reduction of the parasitic losses and the cavity length, within a simplified, robust and compact cavity design.

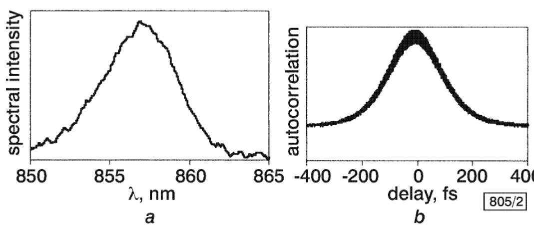

Fig. 2 *Spectrum and autocorrelation for 146 fs pulses at 1 GHz repetition-rate*

a Spectrum
b Autocorrelation

Results: When modelocked in this integrated cavity design, the laser produced pulses of 146 fs duration and 5.4 nm bandwidth (see Fig. 2). These pulses were near transform-limited, having a time-bandwidth product of 0.32. The repetition-rate of 1.002 GHz was measured using a fast-photodiode and a radio-frequency spectrum analyser. No evidence of Q-switching was observed in either the radio-frequency spectrum or in the pulse train observed on a fast oscilloscope. Owing to the low output coupling required for modelocking, the average output power was restricted to ~3 mW, which corresponds to a pulse peak power of 20 W. At lower repetition rates (~650 MHz) a modelocked output power of 46 mW achieved from a similar cavity configuration with a more optimal output coupling of around 1%. Use of such an output coupling at gigahertz repetition rates would require the reduction of the spot size on the SESAM. For the work reported in this Letter, the radius of the spot was set at a conservative 30 µm to avoid any likelihood of damage to the SESAM.

Conclusion: The laser described in this Letter produces what is, to the authors' knowledge, the highest repetition rate from a directly diode-pumped solid-state fundamentally modelocked femtosecond laser. By using Cr:LiSAF and a highly integrated method of dispersion compensation, it has proved possible to generate 146 fs transform-limited pulses, where previous directly diode-pumped fundamentally mode-locked systems have been limited to picosecond pulse durations at high repetition rates [2]. The use of direct diode pumping and SESAM-based modelocking make this a cheaper, more compact and potentially more rugged system than the high repetition rate femtosecond systems based on the more conventional Kerr-lens modelocking (KLM) of other broad-band gain crystals such as Ti:sapphire [9].

It has to be acknowledged that the low stimulated emission cross-section of Cr:LiSAF, and the relatively low output power of the laser-diodes required to pump it, mean that these lasers are unlikely ever to be able to compete on pulse repetition-rate with the directly diode-pumped miniature Nd:YVO_4 lasers, where 8.3 ps pulses have been generated at repetition rates up to 13 GHz [2], or on pulse duration with KLM Ti:sapphire lasers, where 23 fs pulses have been generated at 2 GHz repetition rate [9]. However, as a compromise, which takes something of the short pulse capacity of the latter and combines it with the simplicity, low cost and ruggedness of the former, the laser described in this Letter represents an attractive state-of-the-art option.

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