All-solid-state Kerr lens mode-locked Cr\textsuperscript{4+}:forsterite laser

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Indexing terms: Solid lasers, Laser mode locking

We describe a compact, self-mode-locked, tunable (in the second telecommunication window) all-solid-state, Cr\textsuperscript{4+}:forsterite laser generating transform limited sub 70fs pulses.

The chromium doped forsterite (Cr\textsuperscript{4+}:Mg,SiO\textsubscript{4}) laser has attracted considerable attention as a laboratory test source in that it is broadly tunable in the second optical fibre communications window around 1.35μm. It has a broad absorption peak around 1.1μm and is usually pumped by Nd:YAG lasers operating at 1.06μm. Conventional CW Nd:YAG lasers employ an arc lamp pumping scheme; and the requirements of a complicated heat-exchange cooling system and the considerable electric power consumption (~10kW) consequently restrict this laser to laboratory use. Over the past few years, significant progress has been made in the development of moderately efficient, miniature Nd doped solid state crystal lasers using semiconductor diode bar pumping schemes. The application of such a technology to the Cr:forsterite laser promises a compact, improved efficiency, robust, tunable solid state laser system. Previously, all-solid-state Cr:forsterite laser was reported generating nanosecond pulses pumped by a diode pumped, Q-switched Nd:YAG laser [1]. In this Letter, we describe the first all-solid-state Kerr lens (self) mode-locked Cr:forsterite laser pumped by a CW, high power Nd:YAG, miniature laser, which in turn was pumped by two fibre coupled semiconductor diode laser bars.

First demonstrated in the Tisapphire laser [2], Kerr lens (or self) mode-locking has become the most widely used technique to generate femtosecond pulses from tunable solid-state lasers. It exploits the intensity-dependent nonlinearity of the gain medium which spatially gives rise to the effect of beam self-focusing [3]. For optimised cavity configurations, this optical Kerr effect causes an intensity-dependent gain/loss which favours the operation of mode-locking. Although it mimics the behaviour of a passively mode-locked system incorporating an ultrastable saturable absorber, its nonresonant characteristic (for time scales >-4fs) does not limit the tunability of the mode-locked laser. Soliton-like pulse shaping is achieved when the self phase modulation generated in the gain medium is balanced by negative group velocity dispersion; generation as described here.

The laser employed a symmetrical, four-mirror astigmatically compensated Z-fold cavity with 100mm radius of curvature reflecting mirrors, a flat high reflector and a 1% output coupler. All the mirrors had single-stack dielectric coatings broadly reflecting around 1.25μm. The rectangular Brewster-cut laser rod, 4.5 × 3.0 × 11.5mm long, was indium clad and mounted in a copper jacket water-cooled to temperatures of 8 - 9°C. The 1064nm pump beam, from a CW mini-Nd:YAG laser (Spectra-Physics Model 740-Z-106C), was focused through a folding mirror by a thin lens with 15cm focal length. The crystal absorbed 82% of the pump power corresponding to an absorption coefficient of 1.48cm\textsuperscript{-1}. For an incident pump power of 5.2W, and employing a 0.8 mm intra cavity quartz birefringent filter, the CW tuning range was between 1.204 – 1.334μm, as shown in Fig. 1. In mode-locked operation, the tuning filter was removed and a pair of fused silica Brewster prisms separated by 57cm were inserted to enable dispersion compensation. In this configuration the free-running output wavelength was centred at 1.26μm.

The cavity was first optimised by pumping with a chopped pump beam at a duty cycle of 50:1. Then in truly CW mode, by carefully adjusting the separation of the focusing mirrors and the position of the crystal, very stable mode-locking was achieved. The mode-locking was initiated by a mechanical perturbation (tapping the end mirror) although other techniques are applicable. In this optimised configuration there was no need to insert an intra-cavity slit to obtain Kerr lens mode-locking. The mode-locked laser delivered an average power of 55mW at a repetition rate of 71MHz, and the typical pulse width (FWHM) was measured to be 68fs assuming a sech\textsuperscript{2} intensity profile. The corresponding FWHM spectrum of 24.8nm gave a time-bandwidth product of τ\texttimes\nu = 0.32, indicating that the pulses were effectively transform limited (assuming sech\textsuperscript{2} profiles). Fig. 2 shows a representative pulse spectrum recorded using an optical spectrum analyser with a 0.2nm resolution, and inset is the corresponding non-collinear intensity autocorrelation trace. By translating a slit inserted between the prism and the output coupler, the central wavelength of the mode-locked laser was tuned from 1.24 to 1.30μm.

Through using a diode pumped mini laser, considerable improvement in the amplitude stability of the output mode-locked pulses train was obtained as compared to pumping with a large frame Nd:YAG laser incorporating an unstabilised arc lamp pumping scheme [8]. The pulse energy fluctuated by <1%, as evidenced by the typical output pulse train measured using a fast Ge detector as shown in Fig. 3. By analysing the output RF power spectrum [9], confirmation of the low noise operation was also obtained.

In conclusion, we have demonstrated an all-solid-state femtosecond Cr:forsterite laser tunable from 1.24 to 1.30μm. The pulse width was 68fs with a corresponding spectrum of 24.8nm indicating transform limited operation. The mode-locked laser was very stable in terms of the power fluctuation (<1%). We believe that
Fig. 3 Mode-locked pulse train recorded using a fast Ge detector

with a lower crystal temperature and an optimised higher transmission output coupler, considerably higher average output power should be obtained than the 55mW reported here. Shorter pulse operation can also be obtained if the third order dispersion is minimised. This compact, robust and convenient femtosecond source should have wide applications in spectroscopy and laboratory characterisation of fibre transmission systems in the second telecommunications window. In a similar configuration and pump optimised. This compact, robust and convenient femtosecond source operation can also be obtained if the third order dispersion is minimised. 

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References


DFB laser with integrated waveguide taper grown by shadow masked MOVPE

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A novel DFB laser structure is reported, it has an integrated waveguide taper and has enabled 29% butt coupling efficiency into cleaved standard singlemode optical fibre. The taper is fabricated using a shadow masked growth technique which results in a 2-D mode matching taper structure.

Introduction: Alignment tolerant coupling of laser diodes to optical fibre is essential for the design of low cost optical transmitter modules. The elimination of coupling optics and the use of passive alignment techniques can considerably lower the assembly cost, and recently, tapered lasers have been widely studied as a means of efficient coupling to optical fibre [1–3]. The taper acts as a spot size converter (or beam expander) to ensure that the laser spot size is matched to the ~9μm spot size of standard singlemode fibre, resulting in much improved coupling efficiency and relaxed alignment tolerances which allow the use of passive alignment techniques for the placing of lasers and fibres into the package [4]. Several methods of fabricating beam expansion tapers have been demonstrated recently; the most popular method involving the etching of a lateral taper [1, 2] to achieve mode expansion in both directions, although other methods have also been demonstrated. All these tapered lasers have been Fabry-Perot devices with the exception of a single report of a tapered DBR laser [2]. In this Letter we report the first integration of a beam expanding taper to a DFB laser. The method used for taper growth is the shadow masked growth technique [3].

Laser design and fabrication: The shadow mask growth technique [3] was used to integrate a DFB laser with a passive mode expander for improved fibre coupling. While the structure of the Fabry-Perot version of this device has already been discussed in detail in [3], the present device is different in two respects, first in the provision of an additional layer for the Bragg grating, and secondly, in that the p- and n-doped blocking layers used in [3] were omitted since these require an additional growth step. The growth of the mode expansion taper was performed as follows: a thick layer (~6μm) of InGaAs, followed by a thick InP cap were grown on to an n-type InP substrate, and then patterned by photolithography and selective wet etching to give tapered shadow masks. The masks were 200μm long and tapered exponentially to produce a window which reduces in width from 150 to 5μm, resulting in an optical waveguide which tapers in height and also varies in alloy composition. The active region layer structure comprised four 1% compressively strained InGaAsP quantum wells separated by lattice matched, 1.25μm bandgap wavelength, InGaAsP barriers. This MQW active region and the Bragg grating layer were grown onto the patterned masked substrate. After the shadow masked growth, the shadow mask and the deposited layers on top of it were removed using selective wet etches.

The resulting source wafer was processed into DFB lasers with a buried ridge [5] structure. A Bragg grating was fabricated by holography, the target x being 1.5. The tapered regions were masked off with a thin layer of SO2 during the grating process. After the grating was etched a 1.5μm wide laser stripe was patterned using photolithography, and wet etched through to the n-type buffer layer. The stripe was buried with a heavily p-doped InP current blocking and optical confinement layer and an InGaAs contact layer. Proton bombardment was used to reduce the leakage current path through the InP homojunction. Device fabrication was completed using standard techniques for contact deposition and wafer thinning. To prevent high optical losses caused by absorption, the p-contact and InGaAs cap were removed from the tapered region. The processed wafer was diced to give DFB laser with lengths between 250 and 1000μm integrated with 200μm long tapers extending to the laser facets. Chips were bonded onto copper heat sinks for evaluation. No facet coatings were applied.