# Femtosecond $Cr^{4+}$:YAG laser with a 4GHz pulse repetition rate

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**Abstract:** We report a three-element Kerr-lens modelocked femtosecond $Cr^{4+}$:YAG laser which generated transform-limited 82fs pulses at 1525 nm and a pulse repetition frequency up to 4.02GHz.

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*Introduction:* Progress in the refinement of $Cr^{4+}$:YAG lasers has been ongoing since their initial conception in 1991 [1]. One of the main motivations for this research has derived from the overlap of the operating wavelengths of these lasers with the optical communication windows around 1300nm and 1550nm. The broad absorption band around 1064 nm for $Cr^{4+}$ doped crystals also matches well with several commercially available pump sources. Options include high power Nd:YAG lasers and compact Yb-fibre laser sources, which operate at 1064 nm but its relatively broad absorption band has also made it possible to pump $Cr^{4+}$:YAG with InGaAs diode lasers operating at 980 nm [2]. The fluorescence bandwidth of $Cr^{4+}$:YAG extends from 1200 nm to 1600 nm.. In 2001, Ripin and co-workers [3] accessed around 200 nm of this gain bandwidth and produced pulses with durations shorter that 20 fs. These characteristics underpin the suitability of these lasers to wavelength division multiplexing and optical time division multiplexing. Conveneiently, designs for three-element resonators have also resulted in reductions in laser cavity sizes and proportionate increases in the pulse repetition frequencies. This was first achieved in 1994 by Ramaswamy-Paye and Fujimoto [4], who introduced a technique for dispersion compensation that involved a prismatic end mirror. They reported the generation of femtosecond pulses at a repetition rate of 1 GHz using a Ti:Sapphire laser. This design concept was later adapted for a $Cr^{4+}$:YAG laser by Mellish et al.[5], who reported femtosecond pulses at 1 GHz while Tomaru et al. [6,7] have demonstrated three-element and two-element cavities operating at 1.2 GHz and 2.6 GHz respectively. More recently, we demonstrated a three-element $Cr^{4+}$:YAG laser operating at 3.6 GHz, with a pulse duration of 145fs and producing an average power of 16 mW [8].

In this Letter an improved simple three-element Kerr lens modelocked femtosecond $Cr^{4+}$:YAG laser is reported. A fused-silica, low loss Littrow prism was used for intracavity dispersion compensation. Based on theoretical analysis, this optimised three-element cavity allowed the generation of sub-100fs pulses at repetition rates up to 4GHz at average powers of 100 mW.

*Experimental setup and results:* Figure 1 shows the three-element L-fold cavity configuration. The cylindrical plane-Brewster cut $Cr^{4+}$:YAG laser rod had an absorption coefficient of 2.2 $cm^{-1}$ and was 11.6 mm in length.

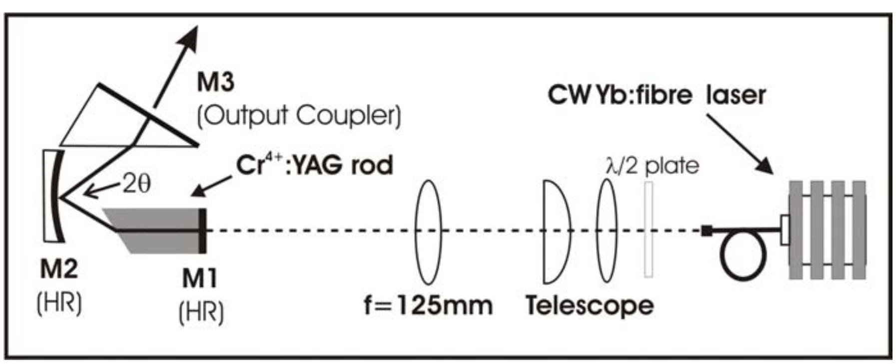


Figure 1. Schematic diagram of KLM $Cr^{4+}$:YAG laser

The plane face of this crystal was coated with a dielectric stack for broadband high reflection (M1) and high transmission at 1550nm and 1064nm, respectively. This crystal was mounted in a water-cooled copper block, which was maintained at a temperature of 14 °C. Three different folding mirrors were used as the second element of the cavity (M2). All the mirrors were highly reflecting at 1550 nm but had different radii of curvatures of -18 mm, -15 mm and -12 mm. The use of each folding mirror depended on the size and the stability criterion of the cavity. A low loss fused silica Littrow prism was used as the terminating element of the cavity. The back face of this prism acted as the output coupler of the system. For the two prisms available coupling efficiencies of 0.3% and 0.5%. were used.

The pump source consisted of a compact IPG Yb:fibre laser capable of producing up to 10 W of near diffraction limited cw laser light at 1064 nm. The pump beam was passed through a λ/2 waveplate which was inserted to direct the pump polarisation into the tangential plane. In order to produce the correct pump beam waist on to the front face of the crystal, the pump beam was passed through a simple telescope system and focussing lens. It is very important to have the correct pump spot size on the crystal face. If the spot size is too large then the intensity inside the crystal is too weak to induce a sufficiently strong optical Kerr effect to initiate and sustain modelocking. On the other hand, if the spot size on the crystal is too small then the focussing is too strong, and a detrimentally large thermal lens is created within the crystal. For this setup, an optimised beam radius (≈35 μm) was incident on the front face of the crystal. From the ABCD matrix formalisation used to calculate the intracavity beam sizes it was calculated that a folding angle (2θ) of 56° was required to compensate for astigmatism in the cavity.

It was found experimentally that 5-6 mm of fused silica was required to provide the correct intracavity negative dispersion for stable modelocked operation. Self-starting modelocking usually occurred at pump thresholds of approximately 2.6 W.

Table 1. Results obtained from 3-element laser

| M2 RoC (mm) | O/C (%) | $\Delta\lambda$ (nm) | $\Delta\tau$ (fs) | $P_{OUT}$ (mW) | Rep. Rate (GHz) |
|---|---|---|---|---|---|
| -18 | 0.3 | 37 | 77 | 60 | 2.4 |
| | 0.5 | 34 | 79 | 167 | 2.3 |
| -15 | 0.3 | 32 | 78 | 60 | 3.05 |
| | 0.5 | 25 | 99 | 104 | 3.02 |
| -12 | 0.3 | 35 | 83 | 41 | 3.71 |
| | 0.5 | 32 | 82 | 85 | 4.02 |

Table 1 gives a summary of the various results that were obtained from the three-element laser. The highest repetition rate of 4.02 GHz was obtained when a –12 mm RoC folding mirror was employed. The best stability was achieved at pump power levels of approximately 5W. Depending on the cavity geometry, the laser would modelock with its centre wavelength between 1505-1550nm and figures 2a,b show the spectrum and autocorrelation for the output pulses from this Kerr-lens modelocked laser when operating at a repetition rate of 4.02GHz.

Assuming a $sech^2$ intensity profile, the pulse duration was determined to be 82fs at a centre wavelength of 1525 nm. With the corresponding spectral width of 32nm, the deduced time-bandwidth product was 0.32, indicating that the pulses were near transform limited. Figure 2c shows the pulse repetition frequency of 4.02 GHz, which was measured using a fast-photodiode and a radio-frequency spectrum analyser. This result was achieved with the 0.5% output coupler in place and an average output power of 85mW was measured.

This laser, when operating at a repetition rate of 2.67GHz, has already been successfully used as a source for datacomm-based system evaluations [9]. Further optimisation of cavity parameters has the potential to offer yet higher pulse repetition frequencies together with increased stability and output power levels.

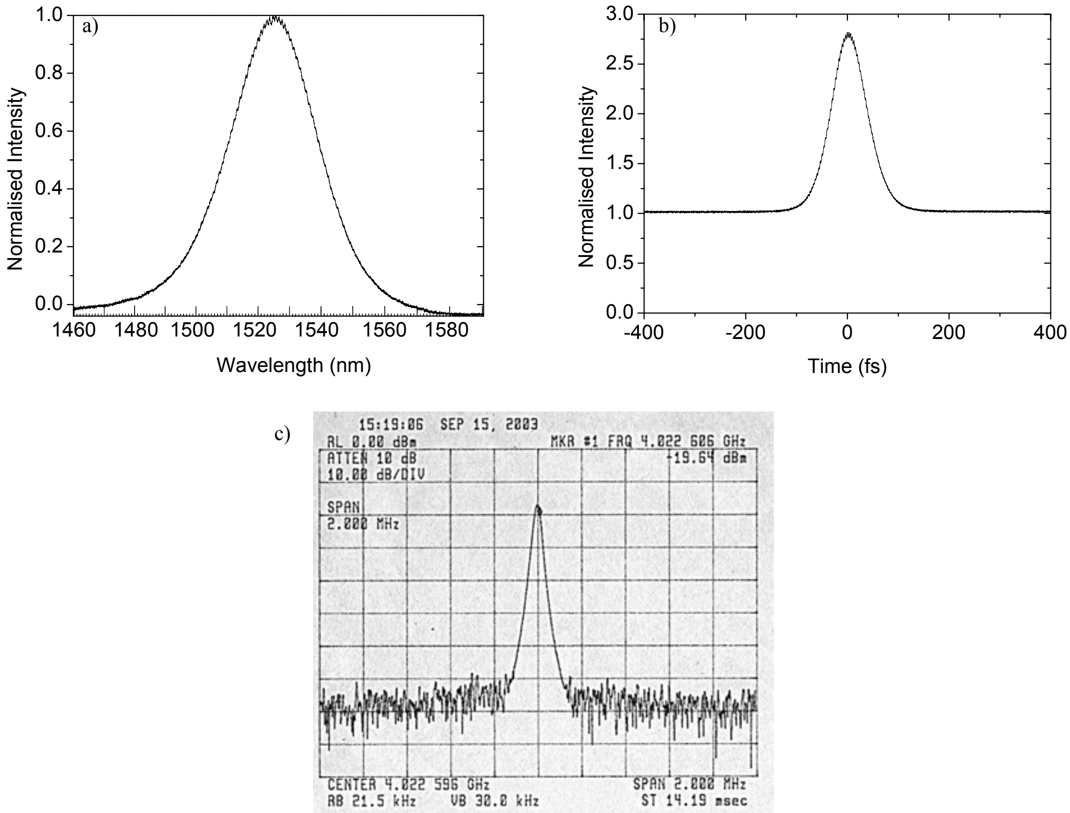


Figure 2 a) Spectral trace, b) Autocorrelation and c)Frequency trace of laser running at 4.02 GHz

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