Letter

Femtosecond pulse generation from a synchronously pumped, self-mode-locked Cr$^{4+}$:YAG laser

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Abstract. Wavelength tuneable pulses of about 100fs duration have been generated through self-mode-locking initiated by synchronous pumping of a c.w. Cr$^{4+}$:YAG laser.

Over the past few years considerable research interest has been directed towards Cr$^{4+}$-doped crystals as sources of wavelength tuneable radiation in the near-infrared region of the spectrum [1, 2]. Since these materials exhibit efficient room temperature operation they should preferentially replace cryogenic colour centre lasers at similar wavelengths. Of particular relevance is Cr$^{4+}$:YAG, which has been shown to operate in the important 1.34–1.6 µm region [3, 4]. The upper-state lifetime (3.6 µs) and cross-section of the laser transition ($8 \times 10^{-19} \text{cm}^2$) of Cr$^{4+}$:YAG are close to those of Ti:sapphire and clearly similarities in laser performance should be expected. One of the most notable characteristics of widely tuneable solid-state laser materials is the self generation of ultrashort pulses, which was initially demonstrated for Ti:sapphire [5], through the so-called Kerr lens mode-locking technique. This has been extended and demonstrated for several solid state laser systems [6]. Femtosecond pulse generation has been reported using Cr$^{4+}$:YAG [7, 8]; however, in general an additional mechanism is required to initiate the self-mode-locking process. Most commonly, this is accomplished through the introduction of an intra-cavity acousto-optic modulator or via a mechanical disturbance to a cavity component, thus affecting the cavity $Q$. It has also been shown that synchronous pumping of Ti:sapphire [9] and Cr$^{4+}$:forsterite [10] can lead to extreme pulse narrowing and femtosecond pulse generation. In these cases the synchronous pumping alone leads to very weak pulse shaping since the process of gain saturation is insignificant; however, the initial amplitude modulation established is sufficient for Kerr lens mode locking to proceed as a result of the nonlinearity due to the power of the relatively long primary pulses established through the synchronous pumping process. In this letter we report the generation of wavelength tuneable pulses of around 100fs generated through synchronous pumping of a Cr$^{4+}$:YAG laser.

A schematic of the laser arrangement is shown in figure 1. Synchronous pumping was provided by a c.w. arc lamp-pumped acousto-optically mode-locked Nd:YAG
laser operating at 1.06 µm, providing a maximum average output power of 8 W in 100 ps pulses at a 100 MHz pulse repetition rate. A conventional, four mirror astigmatically compensated z-fold cavity was used. The mirrors M₁–M₃ were nominally 100% reflecting over the spectral range 1.4–1.6 µm, while the output coupler M₄ had a transmission of 0.5% above 1.5 µm. Below 1.5 µm the reflectance of M₄ decreased rapidly; this acted to ensure laser action only to the long wavelength side of the gain of the Cr⁴⁺:YAG. We have previously shown that the effect of absorption resonances below 1.5 µm owing to the presence of intra-cavity environmental water vapour precludes femtosecond operation, as a result of the large uncompensatable dispersion associated with such resonances. Femtosecond operation throughout the complete Cr⁴⁺:YAG gain band could be obtained by removal of the water vapour or purging the laser system. The Brewster–Brewster Cr⁴⁺:YAG crystal (commercially available from IRE-Polus) was 20 mm long, 6 mm in diameter, indium clad and placed in a copper cooling jacket. At the peak operational pump power densities, the absorption coefficient at 1.06 µm was measured to be 1.05 cm⁻¹.

The gain medium was placed between the 100 mm radius of curvature mirrors M₁ and M₂ and was pumped via M₁ using a 100 mm focal length lens L. Over the wide range of operational pump powers used it was necessary to readjust the positions of the folded section mirrors to compensate for changes in the thermal lensing of the Cr⁴⁺:YAG crystal. Mirror M₂ was also placed on a translational stage, which permitted the slave laser cavity length to be matched to that of the master pump laser with the sub-micron precision usually required to obtain optimized synchronous mode locking. A matched pair of fused quartz Brewster-angled prisms were incorporated intracavity with an apex–apex separation of 20 cm in order to control the overall dispersion of the laser cavity. Tuning of the laser was accomplished by placing a slit S₂ between the prisms where the wavelength of operation could be selected from the spatially dispersed spectrum. A slit S₁ was also placed adjacent to the output mirror M₄ to enhance intensity stability and the Kerr lens mode-locking mechanism, through the preferential spatial selection of the more intense, optimally focused radiation.

By matching the optical length of the Cr⁴⁺:YAG laser to that of the pump synchronous mode locking was observed with the generation of narrow-band spectra and pulses in the 100–200 ps range. Through the precise adjustment of the relative position of the gain medium and the folded-section mirrors M₁ and M₃,
self-formation of femtosecond pulses was obtained, initiated by the synchronous pumping.

Figure 2(a) shows a representative background-free second harmonic intensity autocorrelation of the cavity optimized, self-mode-locked pulses generated by the Cr\textsuperscript{4+}:YAG laser. Also shown in figure 2(b) is the corresponding spectrum of the 110 fs pulses, which with a bandwidth of 23.1 nm infers a time–bandwidth product of 0.33 relatively close to the transform limit of 0.315 for sech\textsuperscript{2} pulses. For pump powers of 7.0 W absorbed in the crystal, an average output power of 40 mW (0.5% output coupler) with pulse durations around 100 fs was obtained.

This femtosecond, self-mode-locked laser was self starting and the output in terms of pulse duration was stable in the long term (hours). Evidence of the role played by the Kerr lensing mode-locking mechanism was clearly illustrated in that once femtosecond operation was established, the laser cavity length could be varied through translation of mirror M\textsubscript{3} by up to \( \sim 1 \) cm from the match point without significant change to the duration of the measured output femtosecond pulse widths. Intensity stability in the output was correlated to fluctuations in intensity of the unstabilized pump laser. Pulse durations of around 100 fs were obtained over a tuning range of 1.50–1.56 \( \mu m \).

In conclusion, we have directly demonstrated for the first time a simple, self starting, tuneable, femtosecond source based on a synchronously pumped Cr\textsuperscript{4+}:YAG laser operating at room temperatures.
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References