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## 1. Introduction

Recent advances in mode-locked solid-state lasers have resulted in pulses as short as 8.5 fsec in the 800 nm region from Ti:sapphire oscillators [1]. Using similar techniques, sub-50 fsec pulses [2-4] have been generated in another solid-state laser system, Cr:forsterite, which operates in the 1.2 to 1.3  $\mu\text{m}$  range. We report here results from both a regeneratively-initiated and self-initiated, mode-locked Cr:YAG laser [5] which is tunable from 1.51 to 1.53  $\mu\text{m}$ . One hundred and twenty femtosecond, nearly transform-limited pulses have been generated with peak output powers of 45 kW. The stable, high peak power pulses and room temperature operation of this laser make it a very suitable alternative to the cumbersome, cryogenic mode-locked NaCl laser [6] commonly used in both narrow bandgap semiconductor and optical communications research.

Lasing action in chromium-doped yttrium aluminum garnet (Cr<sup>4+</sup>:YAG), first reported by Shestakov [7], occurs over the wavelength range from 1.34 to 1.60  $\mu\text{m}$ . Due to the broad tunability, Cr:YAG is a good candidate for femtosecond pulse generation. Active and moving mirror mode-locking of a Cr:YAG laser have resulted in 26 psec and 3 psec pulses at 1.44  $\mu\text{m}$  [8,9], respectively. However citing poor crystal quality resulting in low intracavity power, Kerr lens mode-locking was unachievable and consequently femtosecond pulse generation was not observed.

## 2. Experimental Results

We have constructed a folded, astigmatically compensated z-cavity laser cavity which has been detailed elsewhere [5]. With no intracavity elements present, an absorbed pump power slope efficiency of 15% with threshold of 1.04 W was measured with the output of the laser centered at 1.45  $\mu\text{m}$ . Continuous wave output power of 840 mW was obtained. With the inclusion of intracavity elements (A.O.M. and the prism pair), the slope efficiency dropped to 10%, and the output laser shifted to 1.49  $\mu\text{m}$ , mainly due to wavelength dependent absorption and scattering from surface imperfections in the intracavity elements. The threshold absorbed pump power increased to 1.82 W.

To initiate mode-locking, 4% of the output beam was picked off via a beamsplitter and sent to an InGaAs photo diode which detected the cavity mode beating signal. The signal was frequency-divided and amplified with adjustable phase shift to drive the A.O.M. that had 0.4% modulation depth. Optimization of the cavity to produce self focusing and induce Kerr nonlinearities resulted in a femtosecond pulse train. Figures 1(a) and 1(b) show the background-free intensity autocorrelation and the spectrum, respectively, of the mode-locked pulses. Assuming a  $\text{sech}^2$  intensity profile the pulse width was measured to be 120 fsec. A simultaneous measurement of 20.8 nm spectral bandwidth yielded a time-bandwidth of 0.327 verifying that the pulses were nearly transform-limited. The onset of mode-locking resulted in the peak wavelength to shift to 1.52  $\mu\text{m}$  and a reduction in output power from 460 mW to 440 mW. By placing an aperture between the prism and the high reflector, the output wavelength could be tuned over the range from 1.51 to 1.53  $\mu\text{m}$ . Operation to longer wavelengths was inhibited by the optics coatings. At shorter wavelengths, tuning resulted in the collapse of the broad spectral bandwidth resulting in approximately 20 psec pulses. Losses introduced by atmospheric water absorption together with excited-state absorption (ESA) in the Cr:YAG crystal are the dominant factors inhibiting femtosecond pulse formation at shorter wavelengths (below 1.48  $\mu\text{m}$ ). The role of ESA as a net negative saturable absorber quenching self-mode-locked operation has been studied and suggested previously [8,10].

With the A.O.M. turned off, self-sustained operation in excess of one hour was observed. The measured peak power and energy per pulse were 45 kW and 5.4 nJ, respectively. A threshold output power of approximately 100 mW was required to observe the onset of femtosecond pulse formation (self or Kerr lens mode-locking) corresponding to 1 MW intracavity peak power. In a separate experiment, the A.O.M. was removed from the laser and self-mode-locking was initiated without applying any periodic perturbation to the cavity round-trip gain. In this case, the mode beating signal detected by the InGaAs detector was maximized by adjusting the curved mirrors around the laser rod and the cavity was slightly misaligned to initiate the femtosecond pulse train. Alternatively, one of the prisms could be slightly translated to initiate the pulse train. The output pulse characteristics were indistinguishable from the regeneratively-initiated case.

### 3. Conclusions

As mentioned previously, the femtosecond laser source described here should serve as a fascile replacement to the cumbersome NaCl color center laser. Additionally, the femtosecond Cr:YAG laser should lend itself beautifully to an all solid-state system, either being pumped by a diode pumped Nd:YAG or Nd:YLF laser or alternatively a high power diode laser operating at 980 nm.

### 4. Acknowledgments

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*Added note in proof:* The Imperial College group has obtained 70 fsec pulses with 120 mW of output power and has also identified atmospheric water absorption as an inhibiting factor in femtosecond operation of Cr:YAG below 1.48  $\mu\text{m}$ .

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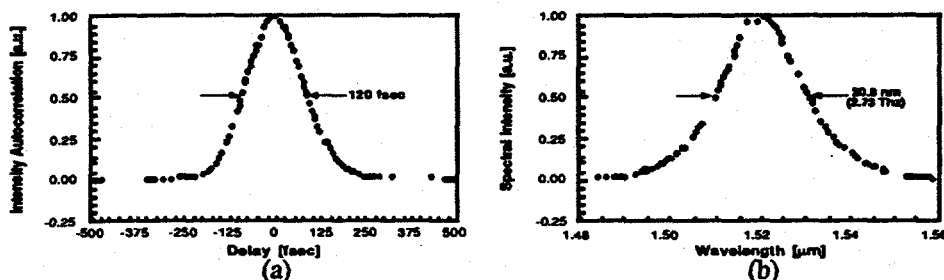


Figure 1. (a) The background-free autocorrelation, and (b) spectrum of mode-locked pulses.