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EFFICIENT FREQUENCY DOUBLING OF A SELF-STARTING ADDITIVE-PULSE MODE-LOCKED DIODE PUMPED Nd:YAG LASER

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ABSTRACT

Using a 1W laser diode pump, Nd:YAG and Nd:YLF lasers have been passively mode-locked using a coupled nonlinear external cavity, to give a stable train of pulses. Pulsewidths as short as 2.0ps have been achieved in Nd:YAG, and 1.4ps in Nd:YLF, with average powers of 110mW. The output of the Nd:YAG laser has been frequency doubled using MgO:LiNbO$_3$ in an external resonant enhancement cavity. An overall energy conversion efficiency of 56% yielded 63mW of average power in bandwidth-limited 2.0ps pulses at 532nm.

INTRODUCTION

The use of feedback from a resonant nonlinear external cavity to shorten the pulses from a mode-locked laser is a powerful and well established technique [1]. Of the nonlinear media exploited to date, the single mode optical fibre has proved to be the most effective. In the time domain, a pulse from the main laser experiences an intensity dependent phase shift in the fibre. Interferometric recombination at the output coupler with the pulse circulating in the main laser, with the correct relative phase, results in constructive interference at the peak of the pulse, while the wings of the pulse destructively interfere. The termination of the laser into a low finesse resonant nonlinear Fabry-Perot can be lumped into a variable reflectivity output coupler. Interference of the fields circulating in the main laser and the external cavity at the output coupler produces a round trip phase dependent reflectivity. The nonlinearity in the fibre causes this to be intensity dependent. With the correct phase bias, the peak of the pulse experiences a high reflectivity while the wings of the pulse, which are retarded in phase, experience a reduced reflectivity. This produces the pulse shaping. A higher finesse Fabry-Perot produces a higher reflectivity modulation for a given nonlinear phase shift in the external cavity, and thus stronger pulse shaping.

Initial results were achieved with actively mode-locked lasers. The extension of the technique to achieve self-starting in Ti:Al$_2$O$_3$ was a significant development in the production of ultra short pulses [2]. An initial intensity perturbation resulting from mode beating in the main laser is, in the presence of sufficient nonlinear feedback, progressively shortened on successive round trips, and grows to saturate the gain, resulting in steady state mode-locking [3,4]. By removing the need for some form of active mode-locking, with its associated synchronisation problems, shorter pulse durations were readily achieved, combined with a general simplification of the overall system. The wide applicability of the scheme has been demonstrated by its extension to other solid state gain media such as Nd:YAG [5], Nd:YLF [6] and Nd:Glass [7]. For each of these gain media, the shortest mode-locked pulses have been achieved with self-starting Additive Pulse Mode-locking (APM). Furthermore, the use of laser diodes, with their superior noise characteristics over other pump sources, resulted in further pulse duration reductions [8,9].

Even with modest output powers from diode pumped lasers, their excellent stability can be exploited to give very efficient frequency doubling by using an external resonant enhancement cavity. This has been demonstrated using single frequency [10] and mode-locked fundamental sources [11].

The self-starting APM of diode pumped Nd:YAG and Nd:YLF lasers is described, and resonant second harmonic generation of the Nd:YAG laser. The results confirm the stability of the APM scheme, and demonstrate the capability for high overall efficiency.

MODE-LOCKED Nd:YAG OSCILLATOR

Figure 1 shows a schematic diagram of the mode-locked laser. The laser diode pump source was coupled into the Nd:YAG/YLF rod which was of a plane/Brewster design, the Nd:YLF rod oriented for operation at 1047nm. The main laser cavity was completed by a highly reflecting curved fold mirror, a plane high reflecting fold mirror, and a plane 17% transmission output coupler. The curved mirror was set at an angle of incidence to compensate for the astigmatism of the single intra-cavity Brewster surface [12]. With the nonlinear external cavity blocked, the diode pumped Nd:YAG laser had a threshold of 190mW, and a slope efficiency of 42%, both measured with respect to diode pump power incident onto the Nd:YAG rod. The laser yielded a maximum output power of 250mW in a TEM_{00} mode for 900mW of diode pump incident on the Nd:YAG rod. The Nd:YLF laser gave similar performance.

In this work, the nonlinear external cavity was formed by a beamsplitter of either 65% or 83% reflectivity, a 1m length of single mode non polarization preserving fibre, and a highly reflecting mirror acting as a retroreflector. Efficient coupling into the fibre was achieved using a 0.25P GRIN lens which was AR coated on the front face and coupled to the fibre with index matching fluid on the other, to eliminate spurious reflections. The fibre had a numerical aperture of 0.11 and a core diameter of 6.7μm. The launch efficiency into the fibre was typically >75%. An identical arrangement was used to retroreflect back through the fibre. The retroreflecting mirror was mounted on a low voltage, high extension piezo-ceramic (PZT) for fine control and stabilisation of the external cavity length. The PZT was mounted on a micrometer driven translation stage for coarse control of the external cavity length. With the cavity lengths approximately matched, trains of mode-locked pulses would appear at random, along with large fluctuations in the output power, associated with relaxation oscillations and self Q-switching. Using a stabilisation scheme based on that of Mitschke [13], with the length of the external cavity appropriately adjusted and the relative cavity lengths locked to give the correct phase of feedback, a stable mode-locked pulse train was formed free from relaxation oscillations and self Q-switching.

The pulsewidth was monitored by background-free second harmonic autocorrelation. With an 83% reflectivity beamsplitter, mode-locking threshold fibre. The pulses had a FWHM of 1.7ps assuming a $sech^2$ pulse shape, up to an average output power of 45mW through the beamsplitter. Pumping beyond this level caused the pulse duration to increase, due to excessive self phase modulation in the fibre. Changing to a 65% reflectivity beamsplitter, the mode-locking threshold increased to 100mW coupled into the fibre, at which point the average output power was 70mW through the beamsplitter. The pulse duration was 2.0ps FWHM at the maximum available pump power, only broadening to 3.6ps when very close to threshold . The lasing bandwidth was measured to be 150GHz. The time-bandwidth product of 0.3 is consistent with bandwidth-limited $sech^2$ pulses. The average output power of the system was 110mW, corresponding to a peak power of about 410W. The relative cavity lengths were stabilised to $\lambda/20$, and the amplitude fluctuation in the output was about 1%.

Initial experiments with diode pumped Nd:YLF using a 65% reflectivity beamsplitter have given a 1.4ps pulse duration at 110mW average output power. Mode-locking threshold corresponded to about 40mW average power coupled into the fibre. The Nd:YLF laser was noticeably more stable than the Nd:YAG system, even when operating close to threshold where the Nd:YAG laser would frequently jump out of lock.

ENHANCEMENT CAVITY.

Figure 2 shows a schematic diagram of the enhancement cavity and locking scheme. The cavity takes the form of a planar bow-tie ring configuration. All mirrors were highly reflecting at 1064nm at normal incidence, except for the 20% transmitting input coupler. The rear curved mirror was also highly transmitting at 532nm. The rear plane mirror was mounted on a PZT for cavity length stabilisation. Astigmatism in the cavity was kept to a minimum by keeping the angle of incidence onto the curved mirrors to about 2°. $MgO:LiNbO_3$ was chosen as the SHG crystal for its high nonlinear coefficient and its ability to 90° phase-match 1064nm radiation which relaxes focusing constraints. Also, its type-1 interaction allows easy control of the fundamental polarization, which is essential for efficient resonating of the fundamental radiation. A 3mm long x-grown $MgO:LiNbO_3$ crystal was placed at the tighter intra-cavity focus where the mode radius $(1/e^2)$ was about 40μm. This was anti-reflection coated at both 1064nm and 532nm. The crystal was mounted in an oven operated at 116.2°C for temperature tuned 90° phase-matching of 1064nm radiation. The oven provided a temperature stability of ±0.1°C.

Spatial mode matching of the laser output beam into achieved using a 500mm focal length lens. The free spectral range (FSR) of the enhancement cavity was coarsely matched to that of the main laser using a micrometer driven translation stage.

To lock the enhancement cavity to a peak of its transmission for the mode-locked laser output, the Pound-Drever frequency stabilisation technique was used [14]. A $LiNbO_3$ phase modulator imposed weak FM sidebands on the locked oscillator modes at a frequency of 33MHz. When the phase-locked modes of the oscillator are injected into a matched cavity, the overlapping orders coincide to give a reflection/transmission behaviour similar to that of a single frequency system. The reflected beam from the enhancement cavity input coupler was detected by a fast photo-diode, the output of which was amplified and sent to a double-balanced mixer. By picking off some of the modulator drive power to the double-balanced mixer, a phase-sensitive error signal was derived for locking the enhancement cavity to the laser. To enable a tight lock it was necessary to introduce a high voltage notch filter into the output of the servo electronics at around 3kHz to prevent driving a mechanical resonance of the PZT.

RESULTS

The efficiency of resonant doubling is very sensitive to the losses in the enhancement cavity. With a 5% input coupler and the $MgO:LiNbO_3$ in the cavity, but with no second harmonic generation, the finesse of the cavity was measured to be 94. This corresponds to a total cavity round trip loss, not including the input coupling, of 1.5%. The SHG performance is also sensitive to the choice of input coupling. From the mirror selection available to us, a non AR coated 20% input coupler was found to give the best conversion efficiency.

The ring design is intended to give unidirectional operation of the resonated fundamental. However, coupling of the fundamental into the counter-propagating mode can occur through scattering in the doubling crystal. Feedback from the counter-propagating mode into the laser can disrupt the mode-locking, and some care in the orientation of the $MgO:LiNbO_3$ crystal is necessary to minimise this.

The conversion to the second harmonic was maximised by scanning the enhancement cavity length by applying a voltage ramp to the PZT mounted mirror and maximising the amplitude of the transmitted 532nm fringes. With 110mW of time averaged 1064nm radiation incident onto the enhancement cavity input coupler in 2.0ps pulses, 63mW, of time averaged power at 532nm was obtained through the rear curved mirror. This represents an overall conversion efficiency of 56% of the Nd:YAG output into available 532nm reflection losses is 63%. The FWHM of the autocorrelation was 3.1ps, which corresponded to a pulse duration of 2.0ps, assuming a sech^2 pulse shape. The bandwidth of the 532nm radiation was measured to be 150GHz, giving a time-bandwidth product of 0.3, which agrees closely with that for bandwidth limited sech^2 pulses. The pulse repetition rate was 125MHz, and thus the peak power at 532nm was about 240W. The acceptance bandwidth of 3mm of $MgO:LiNbO_3$ has been calculated to be 150GHz, and our calculations show that no pulse shortening is expected for 2ps sech^2 pulses converting to the second harmonic in this case. The output was in a clean TEM_{00} spot. With the laser cleanly mode-locked, the amplitude fluctuation in the second harmonic output of the enhancement cavity was no more than 1%.

SUMMARY

A 1W diode laser pumped cw mode-locked Nd:YAG laser giving 110mW of output power in 2.0ps pulses, and 45mW in 1.7ps pulses has been demonstrated. A similar system using Nd:YLF as the gain medium produced 1.4ps pulses with 110mW of average power. The Nd:YAG laser has been frequency doubled in an external resonant enhancement cavity using $MgO:LiNbO_3$ with an overall conversion efficiency of 56%, giving 63mW of time averaged power in bandwidth limited pulses of 2.0ps duration. This corresponds to a peak power of about 240W at 532nm.

The pulse durations achieved with the Nd:YAG laser are close to the limit that can be supported by the linewidth in Nd:YAG. The linewidth in Nd:YLF however can support ~900fs pulse durations. The stronger pulse shaping provided by a Michelson interferometer arrangement could produce shorter pulse durations [15].

The $LiNbO_3$ doubling crystal used in these experiments can be replaced by the new nonlinear crystal LBO. With its reduced dispersion and higher damage threshold than $LiNbO_3$ should result in pulse shortening on conversion to the second harmonic as well as increased conversion efficiency at higher powers.

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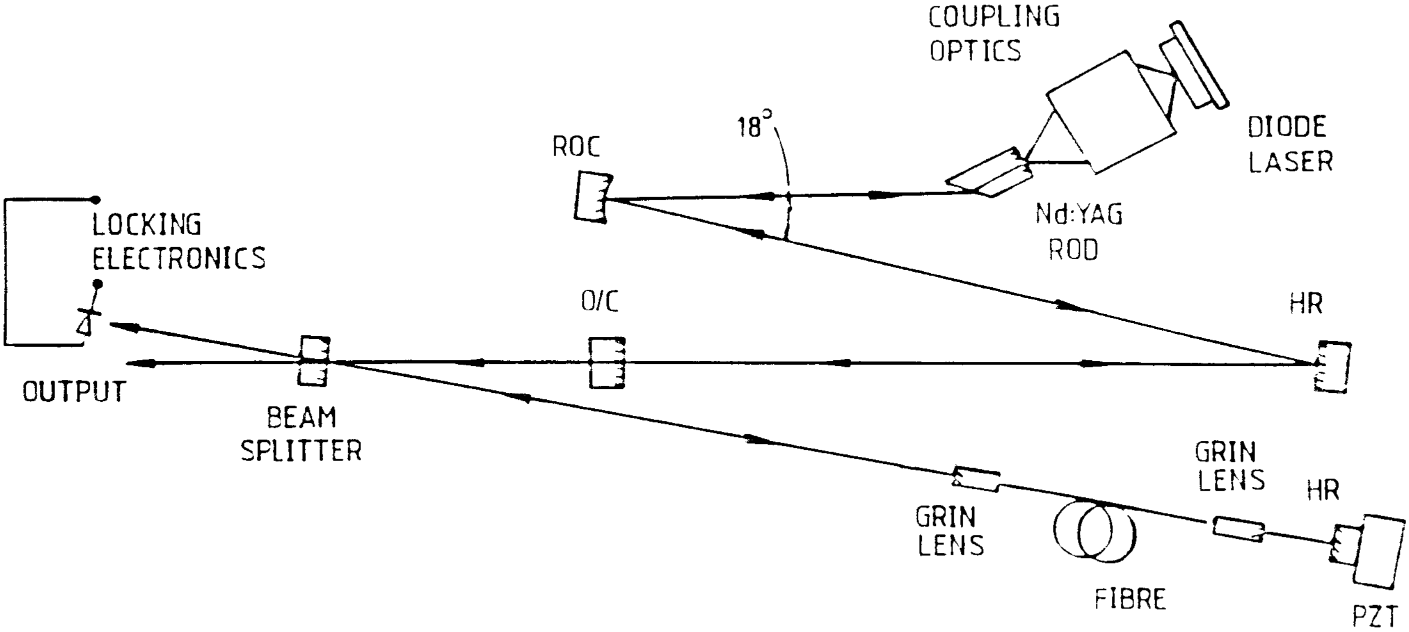

Figure 1. schematic diagram of the mode-locked laser.

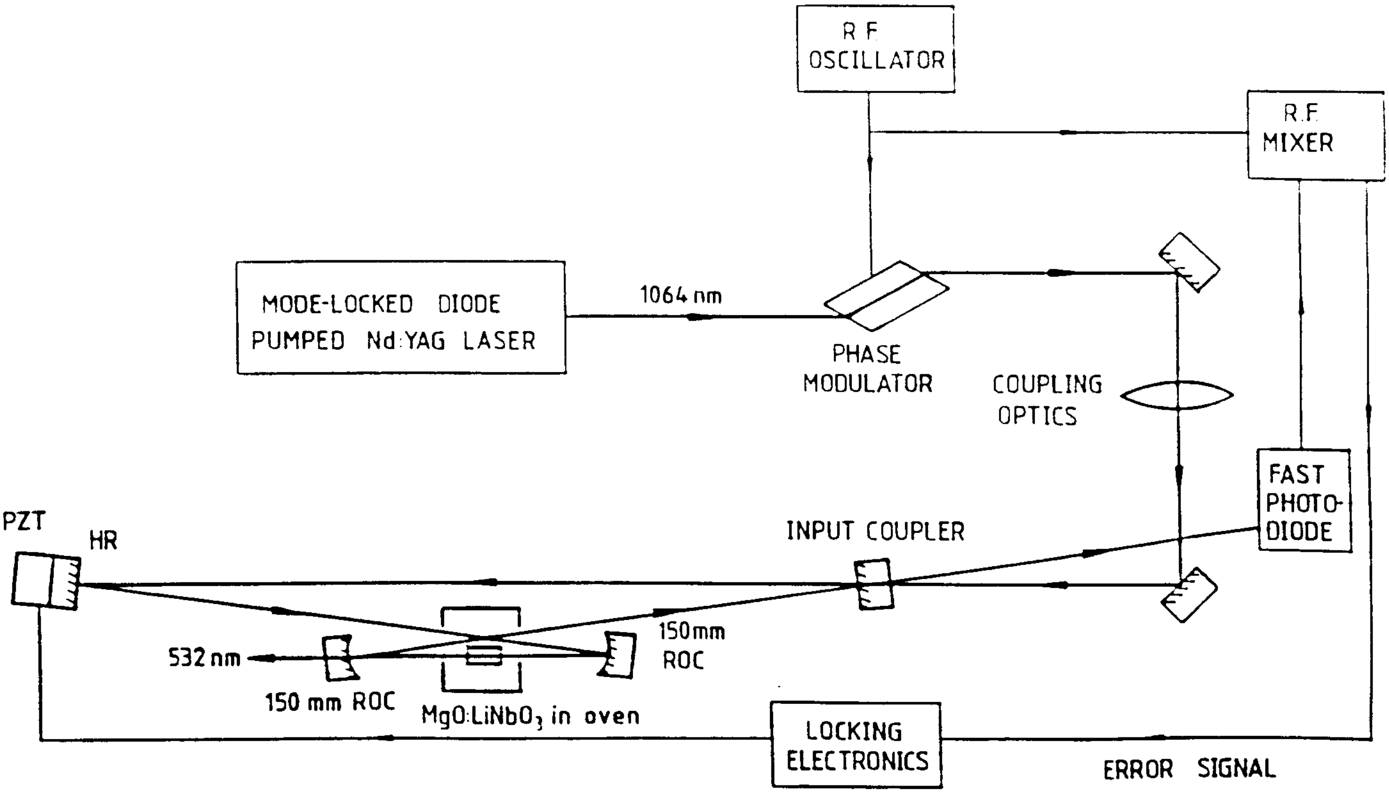

Figure 2. Schematic diagram of the enhancement cavity and the locking electronics