Efficient frequency doubling of a self-starting additive-pulse mode-locked diode pumped Nd:YAG laser

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Using a 1 W laser diode pump, a Nd:YAG laser has been passively mode locked using a coupled nonlinear external cavity to give a stable train of 2.0 ps pulses at an average power of 110 mW. This output has been frequency doubled with an overall energy conversion efficiency of 56%, using MgO:$LiNbO_3$ in an external resonant enhancement cavity, yielding 63 mW of time-averaged power in bandwidth-limited 2.0 ps pulses at 532 nm.

1. Introduction

The continuous wave (cw) mode locked Nd:YAG laser is an important source of high-power, short optical pulses, with a wide range of uses. Operating at its fundamental wavelength in the infrared, or at higher harmonics, it is a convenient pump source for other ultrashort pulse laser systems.

Mode locking of flash lamp pumped Nd:YAG lasers is traditionally achieved by active acousto-optic loss modulation, typically giving 70–100 ps pulse durations at repetition rates of around 100 MHz. By incorporating a thin intracavity etalon at a minimum of transmission, to flatten the gain profile of the Nd:YAG laser transition, Roskos et al. generated pulses of 25 ps duration in a flash lamp pumped Nd:YAG laser [1]. A laser diode pumped Nd:YAG laser, by operating at high modulation frequencies and using the technique of active phase modulation mode locking, has produced pulse durations of 12 ps at a repetition rate of 360 MHz, with a time-averaged output power of 65 mW [2]. With a similar system, using a 1 W diode array, we have recently been able to produce 300 mW of time-averaged output power in 14 ps pulses, at a repetition rate of 260 MHz.

The Nd:YAG laser has also been mode locked passively. By using a second harmonic generation (SHG) element in an anti-resonant ring configuration, spontaneous cw mode locking has been achieved in a commercial flash lamp pumped Nd:YAG laser, yielding pulses of 11 ps duration at 1064 nm [3]. Passive mode locking and self-Q-switching of a Nd:YAG laser using SHG in a coupled-cavity configuration has generated pulses of about 40 ps duration [4].

The technique of self-starting additive-pulse mode locking (APM) has enabled a pulse duration reduction to 6 ps in a cw flash lamp pumped Nd:YAG laser, with almost bandwidth-limited performance [5]. A laser diode pumped Nd:YAG laser, using self-starting APM, has demonstrated pulse durations as short as 1.7 ps with a bandwidth of 0.67 nm, which is essentially the full gain bandwidth of the Nd:YAG transition [6]. This laser diode pumped system operated with a relatively low output power of 25 mW despite using multiple diode pumping.

Even with modest output powers from diode pumped Nd:YAG 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 [7] and mode-locked fundamental sources [8], where, using MgO:$LiNbO_3$ in an external resonant enhancement cavity, conversion from 1064 nm to 532 nm with about 60% efficiency has been observed.

In this paper we describe the resonant second har-

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monic generation of a self-starting APM diode pumped Nd:YAG laser. Our results confirm the stability of the APM scheme, and demonstrate the capability for high overall efficiency. Using a single 1 W laser diode array, we obtained 110 mW of time-averaged output power in stable, bandwidth-limited 2.0 ps pulses at a repetition rate of 125 MHz. This corresponds to a peak power of about 410 W at a wavelength of 1064 nm. This has been frequency doubled in 90° phase-matched MgO:$LiNbO_3$ using an external resonant enhancement cavity. An overall conversion efficiency of 56% was achieved, giving 63 mW time-averaged power at a wavelength of 532 nm in stable, bandwidth-limited 2.0 ps pulses at 125 MHz repetition rate. This corresponds to a second harmonic peak power of about 240 W.

2. Mode-locked Nd:YAG oscillator

Fig. 1 shows a schematic diagram of the mode-locked laser. The laser diode pump source was a 1 W, 200 μm wide array (SDL-2462-P1), which was temperature tuned to the strong absorption line in Nd:YAG at around 807 nm. The laser diode output was collimated using a 6.5 mm focal length compound lens and expanded 4× in the plane of the array using an anamorphic prism pair. The resulting beam was then focussed using a 25 mm focal length aspheric lens. The 10 mm long Nd:YAG rod was polished flat and dielectrically coated to be highly reflecting at 1064 nm and highly transmitting at 807 nm on its rear face, and the intra-cavity face was polished at Brewster's angle to eliminate unwanted etalon effects. The main laser cavity was completed by a highly reflecting 300 mm radius of curvature mirror, a plane high reflecting fold mirror, and a plane output coupler. The output coupler, which had 17% transmission at 1064 nm, was wedged and anti-reflection (AR) coated on its rear face and mounted on a micrometer-driven translation stage. The curved mirror was set at an angle of incidence of 9° to compensate for the astigmatism of the single intra-cavity Brewster surface [9]. The mirror separations were adjusted to give stable operation with an optical path length of 1.2 m, corresponding to a cavity mode spacing of 125 MHz. This long cavity length was chosen to increase the mode-locked pulse energy. With the nonlinear external cavity blocked, the diode pumped Nd:YAG laser had a threshold of 190 mW, 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 250 mW for 900 mW of diode pump incident on the Nd:YAG rod, and the output was in a clean, circular TEM_{00} beam.

Enhanced mode locking through nonlinear optical feedback from an external coupled cavity has been described in detail previously [10,11]. The self-starting APM process relies on the coherent interference at the output coupler between an intensity perturbation circulating in the main laser cavity, and its nonlinearly phase-modulated counterpart circulating in the external cavity resulting in a cumulative shortening of the perturbation on successive round

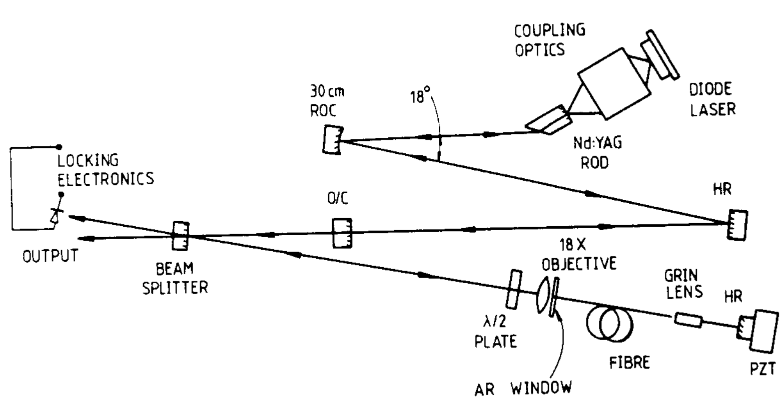

Fig. 1. Schematic diagram of the self-starting APM diode pumped Nd:YAG laser.

trips. The perturbation grows in intensity to saturate the gain in the laser, resulting in steady state mode-locked operation. Self-starting APM is an intensity dependent effect, and in some respects is analogous to passive mode locking with a fast saturable absorber [12,13]. For the mode-locking process to initiate, it is necessary for the perturbation to be subject to some minimum amount of nonlinear phase shift in the external cavity. This determines the mode-locking threshold.

In this work, the nonlinear external cavity was formed by a 65% reflectivity beamsplitter, an 85 cm length of single-mode (at a wavelength of 1064 nm) polarization preserving fibre, and a highly reflecting mirror acting as a retroreflector. The choice of beamsplitter reflectivity and fibre length is a compromise between extracting a large amount of output power, maintaining a suitably low mode-locking threshold and achieving a short pulse duration. Increasing the beamsplitter reflectivity reduces the mode-locking threshold, and permits shorter fibre lengths to be used, but also reduces the available output power. Increasing the fibre length also reduces the mode-locking threshold such that the beamsplitter reflectivity can be reduced, but the steady state mode-locked pulse duration is increased due to the increased dispersion in the external cavity.

Efficient coupling into a polarization eigenstate of the highly birefringent fibre was achieved using a rotatable AR coated half-wave plate and an 18× microscope objective. The fibre had a numerical aperture of 0.14 and a single-mode cut-off wavelength of 1000 nm. The launch efficiency into the fibre was typically 75%. At the rear end of the fibre, the highly divergent monomode output was collimated with a 0.23 pitch graded index lens (GRIN). The retroreflecting mirror was mounted on a low-voltage, high-extension piezo-ceramic (PZT) (Photon Control Ltd. MGE-15) 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. Unwanted reflections at the fibre end faces, which could interfere with the self-starting process, were suppressed using an AR coated window and index-matching fluid (IMF) at the fibre launch end, and IMF at the fibre/GRIN lens interface.

On scanning the length of the external cavity by applying a voltage ramp to the PZT, the output power of the laser was observed to be a sensitive function of the phase of the feedback from the external cavity. This modulation of the output power is due to the interferometric modulation of the effective output coupling of the coupled-cavity laser. While coarsely adjusting the length of the external cavity, it was found that the modulation depth of the output power increased to a maximum as the relative cavity lengths approached exact matching. Near this point, 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. The laser instabilities were caused by relative cavity length changes due to thermal and mechanical fluctuations.

We found that the relative cavity lengths had to be locked together to within a fraction of a wavelength to maintain stable mode-locked operation. To this end, a stabilisation scheme based on that of Mitschke was employed [14]. This takes advantage of the fact that the output power of the coupled-cavity system is a sensitive function of the phase of the feedback, and so in stabilising the system's output power at a certain level, through control of the external cavity length, the phase of the feedback is fixed at a corresponding value.

When the length of the external cavity was 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 background-free second harmonic autocorrelation trace of the pulses had a FWHM of 3.2 ps, which corresponds to a pulse duration of 2.0 ps assuming a $sech^2$ pulse shape. The lasing bandwidth was measured to be 150 GHz. The time–bandwidth product of 0.3 is consistent with bandwidth-limited $sech^2$ pulses. The average output power of the system was 110 mW, corresponding to a peak power of about 410 W at 1064 nm. The relative cavity lengths were stabilised to $\lambda/20$, and the amplitude fluctuation in the output was less than 1%. The mode-locking threshold corresponded to 100 mW coupled into the fibre, and at this point the system output power was 70 mW. The mode-locked pulse duration was observed to be insensitive to the level of operation above threshold, only broadening significantly to 3.6 ps when very close to threshold. The sensitivity of the pulse duration to cavity length mismatch was also investigated, and is illustrated in fig. 2. Detuning to longer external cavity lengths by 160 μm caused the mode locking to break up. With shorter external cavity lengths, detuning to beyond 400 μm brought about a smoother increase in pulse duration to 5 ps.

3. Enhancement cavity

Fig. 3 shows a schematic diagram of the enhancement cavity and locking scheme. The cavity takes the form of a planar bow-tie ring configuration, with two plane mirrors and two curved mirrors of 150 mm radius of curvature. All mirrors were dielectrically coated to be highly reflecting at 1064 nm (99.7%) at normal incidence, except for the input coupler, which was 20% transmitting at 1064 nm. The rear curved mirror was also highly transmitting (95%) at 532 nm. The rear plane mirror was mounted on a PZT for cavity length stabilisation. The PZT was mounted on a translation stage for coarse cavity length control. Mirror separations were adjusted to give an intra-cavity focal spot size of 45 μm between the two curved mirrors, and a corresponding beam waist of 390 μm between the two plane mirrors. Astigmatism

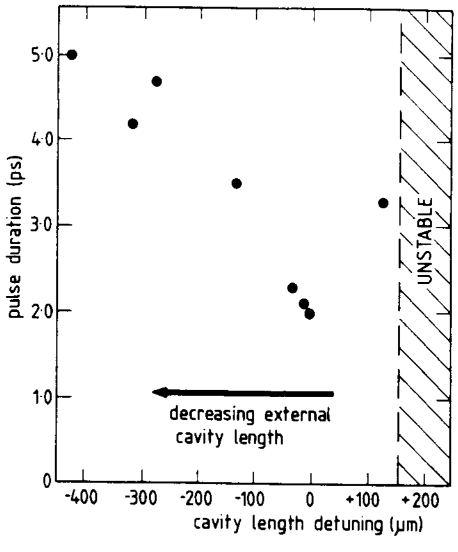

Fig. 2. Graph showing variation of pulse duration with cavity length mismatch.

in the cavity was kept to a minimum by keeping the angle of incidence onto the curved mirrors as small as possible; in practice this was 2°.

The frequency doubling was achieved using a 5×5 mm^2 aperture, 3 mm long x-grown $MgO:LiNbO_3$ crystal. This was anti-reflection coated at both 1064 nm and 532 nm, and was placed at the tighter intra-cavity focus. The crystal was mounted in an oven operated at 116.2°C for temperature-tuned 90° phase matching of 1064 nm radiation. The oven provided a temperature stability of 0.1°C. $MgO:LiNbO_3$ was chosen as the SHG crystal for its high nonlinear coefficient and its ability to 90° phase match 1064 nm radiation, which relaxes focussing constraints. Also, its type-1 interaction allows easy control of the fundamental polarization, which is essential for efficient resonating of the fundamental radiation.

To obtain good coupling of the laser output into the lowest-order spatial mode of the enhancement cavity, and to avoid excitation of higher-order modes, it was necessary to spatially mode match the laser output beam into the enhancement cavity using a 500 mm focal length lens. It was also necessary to match the free spectral range (FSR) of the enhancement cavity to that of the mode-locked laser. 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.

To lock the enhancement cavity to a peak of its transmission of the mode-locked laser output, the Pound–Drever frequency stabilisation technique was used [15], which has been described in detail previously [8]. In this work, a $LiNbO_3$ phase modulator was used to impose weak FM sidebands on the locked oscillator modes at a frequency of 33 MHz. 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. It was necessary to introduce a high-voltage notch filter into the output of the servo electronics at around 3 kHz to prevent driving a mechanical resonance of the PZT and thus enable a tight lock.

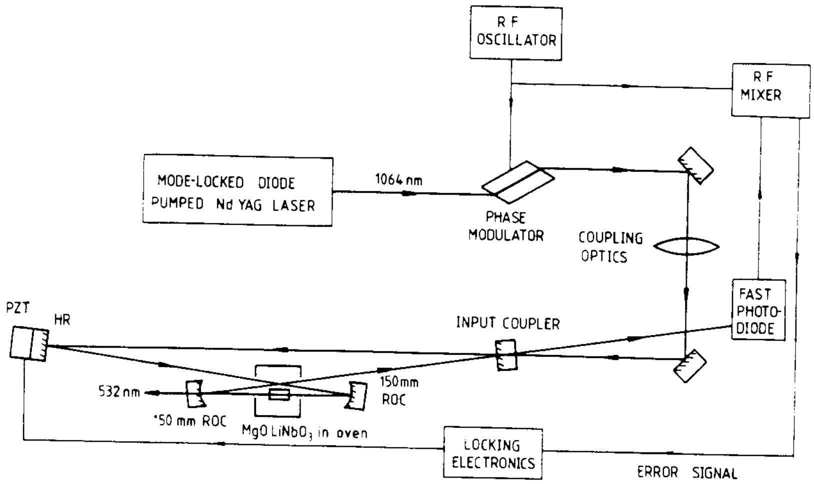

Fig. 3. Schematic diagram of the resonant enhancement cavity and locking electronics.

4. 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. We have observed that 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 optimising the transmitted 532 nm fringes. With 110 mW of time-averaged 1064 nm radiation incident onto the enhancement cavity input coupler, 63 mW of time-averaged power at 532 nm was obtained through the rear curved mirror. This represents an overall conversion efficiency of 56% of the Nd:YAG output into available 532 nm output. The conversion efficiency taking into account reflection losses is 63%. Fig. 4 shows a typical autocorrelation trace of the 532 nm pulses. The fwhm was 3.1 ps, which corresponded to a pulse duration of 2.0 ps, as-

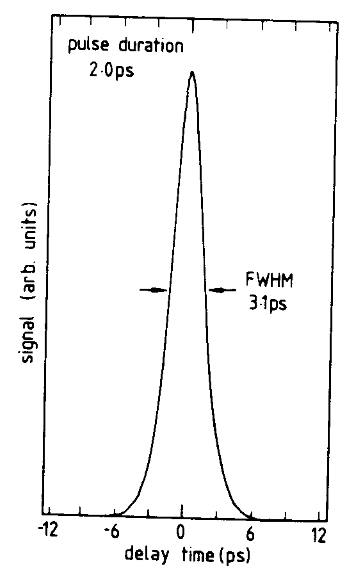

Fig. 4. Background-free autocorrelation trace of the 532 nm pulses. The autocorrelation fwhm is 3.1 ps, giving a pulse duration of 2.0 ps assuming a $sech^2$ pulse shape.

suming a $sech^2$ pulse shape. The bandwidth of the 532 nm radiation was measured to be 150 GHz, giving a time–bandwidth product of 0.3, which agrees closely with that for bandwidth-limited $sech^2$ pulses. The pulse repetition rate was 125 MHz, and thus the peak power at 532 nm was about 240 W. The acceptance bandwidth of 3 mm of $MgO:LiNbO_3$ has been calculated to be 150 GHz, and our calculations show that no pulse shortening is expected for 2 ps $sech^2$ 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%.

5. Summary

We have described a 1 W diode laser pumped cw mode-locked Nd:YAG laser giving 110 mW of output power in stable, bandwidth-limited pulses of 2.0 ps duration. This has been frequency doubled in an external resonant enhancement cavity using $MgO:LiNbO_3$ with an overall conversion efficiency of 56%, giving 63 mW of time-averaged power in bandwidth-limited pulses of 2.0 ps duration. This corresponds to a peak power of about 240 W at 532 nm.

The optimisation of operating parameters in the mode-locked Nd:YAG laser has been far from exhaustive. Thus, improvement in the performance of the oscillator can be expected. Future work will examine scaling of the pump power, and also investigations into the mode-locking process itself, so as to ascertain the scaling laws which apply there. Nonlinear crystals with reduced group velocity dispersion compared to $MgO:LiNbO_3$, such as lithium triborate (LBO) [16] and potassium titanyl phosphate (KTP) [17] are being considered as a replacement for the $MgO:LiNbO_3$ crystal, with a view to further optimising the resonant enhancement cavity.

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