A Laser-Diode-Pumped Nd : Glass Laser: Mode-Locked, High Power, and Single Frequency Performance

David W. Hughes, Mark W. Phillips, John R. M. Barr, and David C. Hanna

Abstract—**We report the performance of a laser-diode-pumped Nd:glass laser. Using the AM active mode-locking technique, pulses as short as 9 ps were obtained. The development of a high power (415 mW), high optical slope efficiency (32.4%) laser-diode-pumped Nd:glass laser using high power, broad stripe laser diodes as the pump source is described. Single frequency operation of the Nd:glass laser, using an acoustooptic modulator to ensure unidirectional operation in a ring laser configuration was investigated. An instantaneous linewidth of less than 300 Hz was observed.**

I. Introduction

NEODYMIUM-DOPED glass is of great interest as a laser-diode-pumped laser medium. Nd : glass has a strong absorption in the region of 800 nm, and so can be readily pumped by commercially available GaAlAs laser diodes. The pump absorption bands of Nd : glass are much broader than those of Nd : YAG or Nd : YLF, so that stringent wavelength control of the pump source via temperature tuning is unnecessary. Traditionally, the Nd : glass laser has been pumped using flashlamp pumping or end pumping using an argon laser operating at 514 nm [1]. The greater compactness and higher efficiency of the laser diode over these other pump sources has resulted in a number of recent publications concerning the laser-diode-pumped Nd : glass laser [2]–[7]. Unlike many other laser hosts, the concentration of neodymium ions can be very high in glass before the onset of severe fluorescence quenching (typically 8 wt% in glass as opposed to 1.3 wt% in YAG). This means that more compact laser resonators can be designed.

The broad fluorescence linewidth of Nd : glass (5.3 THz, 19.6 nm for Schott LG760 Nd-doped phosphate glass) means that the Nd : glass laser is capable of supporting subpicosecond mode-locked pulses. Several authors [3]–[6] have reported active mode locking of the laser-diode-pumped Nd : glass laser using both amplitude modulation (AM) [3]–[5] and frequency modulation (FM) [6] techniques. The Nd : glass laser has also been mode locked using the technique of additive-pulse mode locking (APM) [8]. In the latter case, a krypton ion laser was used as the pump source in order to achieve the necessary output power from the Nd : glass laser for this technique to be self starting. In Section II we present the performance of a laser-diode-pumped mode-locked Nd : glass laser. Acoustooptic amplitude modulation (AM) mode locking was used, yielding a pulse duration of 9 ps.

The main disadvantage of Nd : glass as compared with Nd : YAG is its low thermal conductivity (0.6 W/m/K as opposed to 11 W/m/K). This leads to a number of deleterious effects, including thermally induced birefringence, thermal lensing and physical thermal damage. These problems have, in the past, largely restricted the performance of the laser-diode-pumped Nd : glass laser to relatively low output powers [4]–[6]. Korn *et al.* [7] have surmounted this problem to some extent by using a rotating Nd : glass disk as the gain medium, obtaining output powers as high as 550 mW with an optical slope efficiency of 37%. In Section III we will discuss the use of high power broad stripe laser diodes as an alternative means of obtaining high efficiency, high power operation of the Nd : glass laser with a stationary gain medium. This technique was found to produce a similar output to that obtained using a Ti : sapphire laser as the pump source.

We have also obtained interesting results from a single frequency Nd : glass laser, pumped by a Ti : sapphire laser at 805 nm. Using an acoustooptic modulator as the means of obtaining unidirectional operation [9] from a Nd : glass ring laser, a linewidth of less than 300 Hz has been obtained. To our knowledge this is the narrowest linewidth reported using this technique. The results from this experiment will be briefly reported in Section IV, and it is emphasized that this system is expected to work equally well when pumped with laser diodes.

II. The Mode-Locked Laser-Diode-Pumped Nd : Glass Laser

The mode-locked Nd : glass laser has, as stated previously, been pumped using both flashlamp pumping and end pumping with an argon ion laser. Using the latter approach, Yan *et al.* [1] obtained pulses as short as 10 ps from an AM mode-locked Nd : glass laser. Several authors [3]–[6] have more recently reported the performance of actively mode-locked laser-diode-pumped Nd : glass

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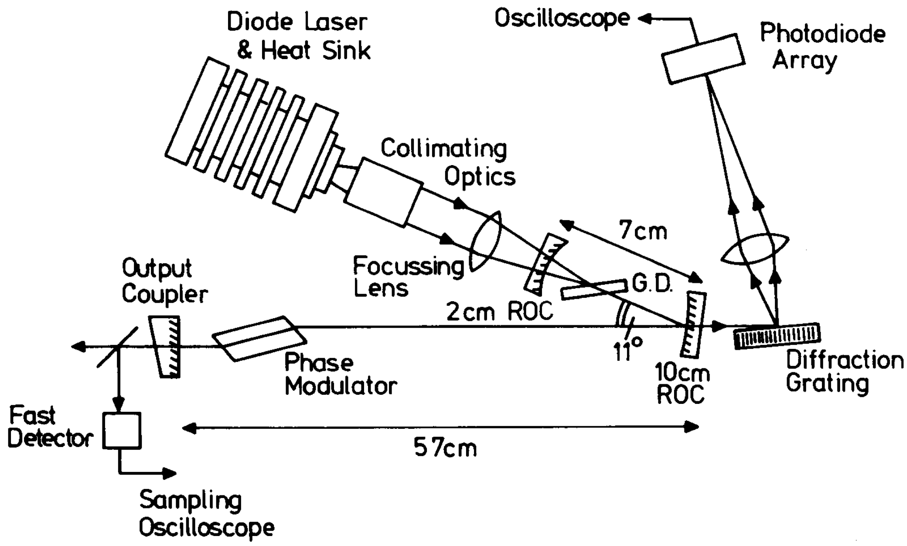

Fig. 1. The mode-locked laser-diode-pumped Nd:glass laser. The laser is shown configured for FM mode locking. GD: Nd:glass disk.

lasers, obtaining pulse durations ranging from 7 ps [4] to 58 ps [5]. In this section, we present results obtained from an actively mode-locked laser-diode-pumped Nd:glass laser, where the AM mode-locking technique has been used.

Fig. 1 shows a schematic of the laser used in these experiments. The pump source was a 500 mW, ten stripe laser diode array (SDL 2432). This was mounted on a heatsink, and temperature tuned using a Peltier cooler in order to achieve maximum absorption of the pump radiation in the active medium. The laser diode output was collimated using a compound lens of focal length 6.5 mm and numerical aperture 0.6 and passed through an anamorphic prism beam expander (magnification $\times 5$). The beam was then expanded using a $2\times$ telescope in order to exclusively pump the TEM_{00} mode of the Nd:glass laser. The pump beam was then focused through the laser cavity rear mirror using a 3.2 cm focal length lens. The collimating and focusing optics were all antireflection (AR) coated at the pump wavelength. The active medium was a 1.2 mm thick, 10 mm diameter disk of highly doped (8 wt%) LG760 Nd:phosphate glass. This thickness of glass was sufficient to absorb more than 90% of the pump radiation. A low insertion loss was achieved by placing the disk at Brewster's angle at the focus of a three mirror astigmatically compensated cavity [10], and was held between two copper plates to aid heat removal. The copper plates were 30 mm $\times$ 20 mm in dimension, with a clear aperture of 8 mm. The Nd:glass disk was pumped at its center. The required angle of incidence on the 10 cm radius of curvature (ROC) turning mirror for compensation of the astigmatism produced by the Brewster angled disk was calculated to be 5.5°. The average TEM_{00} mode size (FWHM) in the active medium was calculated to be 21 μm, taking into account the refractive index of the active medium. The focused pump spot size (FWHM) was 24 μm in the plane of the array and <24 μm in the plane perpendicular to the array (the resolution limit of our measurement was 24 μm). The cavity rear mirror (ROC 2 cm) and the turning mirror were highly reflective (HR) at 1.05 μm ($>99.9\%$ reflectivity) and highly transmissive at 800 nm ($>90\%$ transmission). The output coupler had a reflectivity of 98.5%, and a wedge angle of 10°. The low output coupling was chosen due to the low gain of the Nd:glass laser system, and to allow the insertion of lossy elements (phase and amplitude modulators) into the cavity. The rear surface of each of the cavity mirrors was AR coated at 1.05 μm to suppress unwanted etalon effects.

With no modulator in the cavity, the laser exhibited a threshold of 60 mW absorbed pump power, and an optical slope efficiency of 11%. This slope efficiency is quoted for pump powers below 200 mW. Above 200 mW, the slope efficiency decreased with pump power. We have attributed this decrease to thermally induced birefringence [11].

Amplitude modulation mode locking of the Nd:glass laser was accomplished using an acoustooptic standing-wave modulator (Isle Optics ML120B). This was a Brewster angled fused quartz device placed as close as possible to the laser output coupler. The modulator was driven at a radio frequency (RF) of 120 MHz using an RF synthesizer and broad-band RF amplifier. This corresponded to a laser cavity length of 62.5 cm. With an RF power of 1 W, the diffraction efficiency of the device was measured to be 18.2%. The diffraction efficiency ϵ is related to the modulation depth θ by the expression

$$\epsilon = 0.5[1 - J_0(2\theta)] \quad (1)$$

where $J_0(x)$ is the zero-order Bessel function of x. The modulation depth was thus calculated to be 0.63 at a drive

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power of 1 W. The passive insertion loss of the device in the laser cavity was negligible. However, when the laser was mode locked, the output power was found to drop to about 30 mW (for maximum pump power), which was a decrease of about 15% from the output when the laser was not mode locked.

The mode-locked laser output was observed using a fast photodetector (GE Y-35-5252 25 GHz photodiode) and a Tektronix sampling scope. The observed pulse duration (50 ps) was seen to be limited by the response of this combination. For more accurate measurements, a standard nonbackground free-autocorrelation technique was used. The moving prism in the autocorrelator was scanned at a rate of up to several Hertz. A KTP crystal was used for second harmonic generation. A typical autocorrelation trace is shown in Fig. 2. If we assume a Gaussian temporal profile, the width of 13 ps (FWHM) of this autocorrelation trace corresponds to an optical pulse duration of 9 ps. This pulse duration was observed for an RF drive power of 0.8 W. The diffraction efficiency of the modulator at this power was 13.8%. It should be noted that for 9 ps pulses to be obtained, extremely careful adjustment of the orientation of the modulator had to be carried out in order to optimize the Bragg angle.

In a previous paper, Krausz *et al.* [4] have reported slighter shorter pulses (7 ps) than those reported here from a similar laser-diode-pumped AM mode-locked Nd : glass laser. However, in that paper, the shortest (7 ps) pulses were only observed at pump powers slightly above threshold. At higher pump powers (corresponding to an average output power of 40 mW) the pulse duration increased to 20 ps. The authors suggested that this may be due to self-phase modulation (SPM) in the active medium. In our experiments, we have observed no such change in the pulse duration with pump power.

The optical spectrum of the laser was monitored using a 1800 lines/mm diffraction grating spectrometer. The free-running spectrum had a FWHM of 7.5 GHz as shown in Fig. 3(a). When the laser was mode locked such that the 9 ps pulses were obtained, the spectrum FWHM increased to 80 GHz as shown in Fig. 3(b). This yields a time-bandwidth product of 0.72 which is 1.6 times transform limited. Unlike in the work of Krausz *et al.* [4], we observed no modulated structure on the mode-locked optical spectrum. We did, however, observe heavily modulated and shifted optical spectra as the modulator frequency was detuned from its optimum mode-locking value (i.e., the value which yielded the shortest pulse).

We have previously reported FM mode locking of this laser [6], where we also obtained 9 ps pulses. We have thus observed no significant difference between the pulse durations obtained using AM and FM mode locking. This is in contrast to the results of Maker *et al.* [12], [13] who carried out experiments on the active mode locking of a laser-diode-pumped Nd : YAG laser. They obtained significantly shorter pulses for FM mode locking than for AM mode locking (12 ps as opposed to 55 ps). The reason for this was not fully understood. One point which should be noted, however, is that the laser cavity used for the Nd : YAG laser was markedly different to ours, with the gain medium adjacent to the cavity rear mirror. This leads to a much broader free-running linewidth than we have seen in our experiments. This broadening has been attributed to spatial hole burning [14].

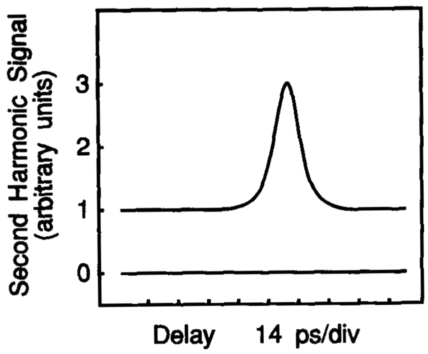
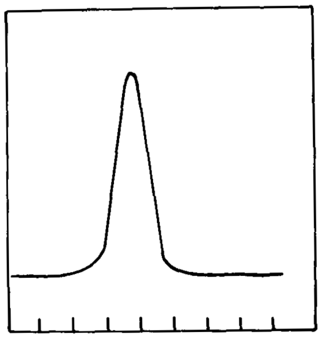
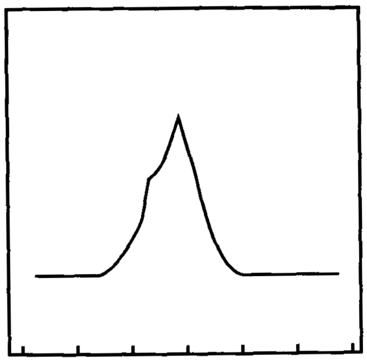


Fig. 2. A typical AM mode-locked autocorrelation trace of duration 13 ps.



(a)



(b)

Fig. 3. (a) Free running laser spectrum. Scale 7.5 GHz/div. (b) AM mode-locked laser spectrum. Scale 75 GHz/div.

III. High Power Operation of the Laser-Diode-Pumped Nd : Glass Laser

As was mentioned in the introduction, one of the main disadvantages of the Nd : glass laser is its low thermal

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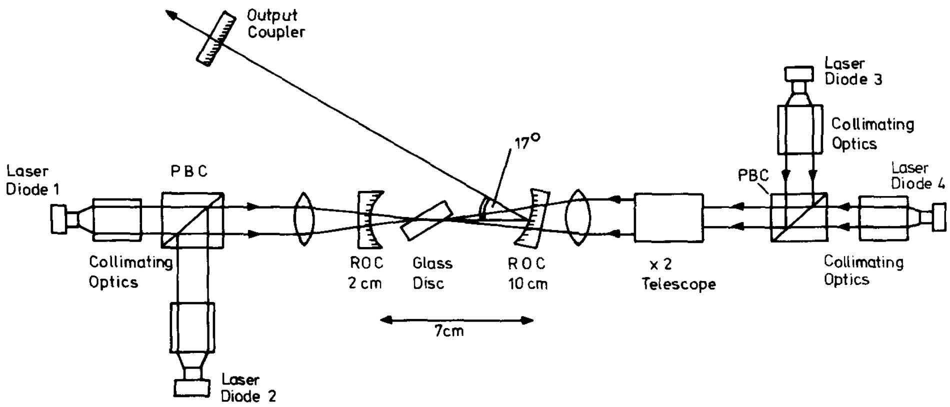

Fig. 4. Nd:glass laser pumped by four broad stripe laser diodes. PBC: Polarizing beam splitting cubes.

conductivity, which restricts high power operation. High efficiency operation (42% optical slope efficiency) has been reported using a single stripe laser diode as the pump source [2]. Due to the low power of the pump source, however, the laser output did not exceed a few milliwatts. Higher output powers (tens of milliwatts) have been reported using laser diode arrays as pump sources [4]–[6], but this in turn leads to lower slope efficiencies due to the poorer match between the focused pump beam and the Nd:glass laser cavity mode. The problem is compounded by thermal considerations, especially thermally induced birefringence and thermal physical damage [11]. Thermally induced birefringence causes a decrease in the laser efficiency as the pump power is increased, for a laser with a polarization selective element. We have also found that the highly doped glass used in our initial experiments melted at the pump input face at a pump power of about 600 mW (obtained by polarization coupling two 500 mW laser diodes) so that no significant increase in output power could be achieved simply by increasing the pump power. In this section we describe the performance and design of a laser-diode-pumped Nd:glass laser which has an output power of 415 mW and an optical slope efficiency of 32.4%.

The incentive behind this work is again to obtain short mode-locked pulses. There is currently much interest in the technique of additive pulse mode locking (APM). This is a technique in which a portion of the laser output is directed into an external cavity containing some nonlinear element. This portion of the output suffers a nonlinear phase shift or a nonlinear amplitude change, and, provided the cavity lengths are properly matched, can interfere interferometrically with a pulse circulating in the main laser cavity. This can result in the pulse in the main laser cavity being shortened. This technique has been shown to be self-starting in several laser systems, e.g., Nd:YAG [15], [16], Nd:YLF [17], and Nd:glass [8]. In each case, an intensity dependent threshold has been observed for the onset of self-starting APM. Krausz *et al.* [8] reported that a laser output of about 250 mW was necessary for stable mode locking to be achieved in the Nd:glass laser (it is thus necessary to increase dramatically the powers obtained from the laser-diode-pumped Nd:glass laser if subpicosecond APM operation is to be achieved from this all solid-state system).

We have previously reported the use of high power broad stripe laser diodes to pump the Nd:glass laser described in Section II [11]. Two 500 mW broad stripe laser diodes (STC LQ-(P)-05) pumped the laser, one through the cavity rear mirror and the other through the turning mirror. This double end pumping allowed us to obtain a more uniform longitudinal heat distribution throughout the glass disk, and with more careful heatsinking to reduce the effects of thermally induced birefringence, we obtained an output power of 153 mW (with an output coupling of 5%). However, no further significant increase in output power could be obtained due to the glass melting.

To combat this problem, and to enable us to pump the laser with four laser diodes, we have carried out experiments using a lower doped glass (4 wt%) which gives an increased volume in which the heat is dissipated. The experimental arrangement is shown in Fig. 4. The collimating optics for all four diodes were identical to that described in Section II, but a prism beam expansion of $\times 6$ was used. Laser diodes three and four were focused through the turning mirror using an AR coated lens of focal length 7.5 cm. A $2\times$ telescope was used to expand the beams from laser diodes three and four to ensure single transverse mode operation of the Nd:glass laser. The 2.4 mm thick glass disk (this thickness was sufficient to absorb 95% of the incident pump radiation) was held between two copper plates, and indium foil (75 μm thick) was placed between the glass and the copper to ensure good thermal contact. The copper plates were as described previously, but the clear aperture was now reduced to less than 3 mm. The angle of incidence of the turning mirror was now increased to 8.4° to take into account the increased thickness of the glass disk. The average Nd:glass laser mode size (FWHM) in the active medium was calculated to be 22 μm. The focused pump spot

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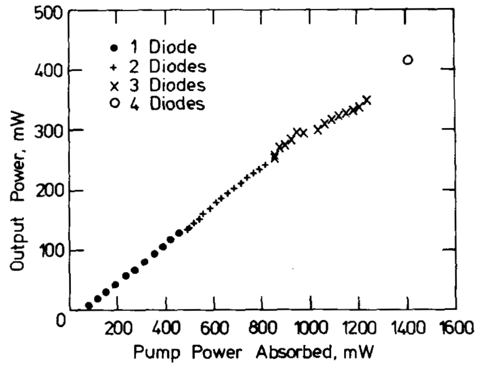

Fig. 5. Laser-diode-pumped Nd : glass laser performance with 5% output coupling.

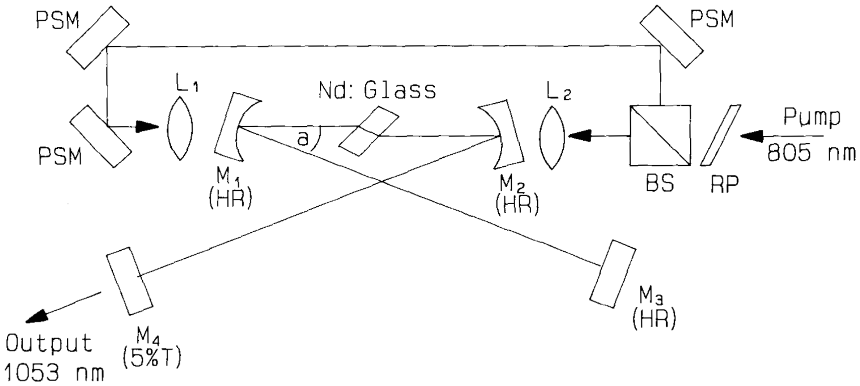

Fig. 6. Ti : sapphire pumped Nd : glass laser. PSM: Pump steering mirror. RP: Retardation plate. BS: Beam splitter. Angle (a): 16.8°.

size was measured to be <24 μm in both the vertical and horizontal planes. The output coupling was 5%. This output coupling was not optimized for maximum output power.

The performance of this laser when pumped with four laser diodes is shown in Fig. 5. The laser threshold is 50 mW of absorbed pump power, and the slope efficiency 32.4%. The maximum output power was 415 mW for an absorbed pump power of 1.4 W. There was no decrease of laser output power with time, and the laser output was at all times TEM_{00}. As stated previously, thermally induced birefringence can cause a decrease in slope efficiency due to depolarization of the intracavity beam and increased loss from the Brewster surfaces. We monitored the Brewster reflections as a function of pump power, and observed the expected quadratic dependence of reflectivity with pump power consistent with losses due to thermally induced birefringence [18]. However, at maximum pump power, the reflected signal amounted to no more than 4% of the laser output power, demonstrating that in this laser, thermally induced birefringence introduces negligible losses. This is further confirmed by the fact that no evidence was observed of a decrease in slope efficiency with increasing pump power. The laser output was found to be very well polarized. When passed through a polarizing beam splitter, the ratio of light transmitted to that rejected was $\sim 2000:1$.

We have compared the laser-diode-pumped performance of the Nd : glass laser with that of a Ti : sapphire pumped system. The laser cavity arrangement for the Ti : sapphire pumped Nd : glass laser was slightly modified in order to facilitate switching from a standing wave configuration to the ring configuration required for single frequency operation (see Section IV). The standing wave cavity configuration is shown in Fig. 6.

The output of the Ti : sapphire laser was split into two equal intensity beams to allow symmetrical double end pumping. The beams were focused into the Nd : glass disk using two AR coated lenses (L_1 and L_2) of focal length 7.5 cm. The mirrors M_1 and M_2 (both 10 cm ROC) were highly reflective ($>99.9\%$) at the laser wavelength and highly transmissive ($>90\%$) at the pump wavelength. The laser resonator was completed using a highly reflective mirror M_3 and a 5% transmitting output coupler M_4.

The threshold for lasing in the Ti : sapphire pumped system was 84 mW of absorbed pump power (42 mW in each direction). The output of the laser increased linearly with pump power, producing 480 mW of CW power for

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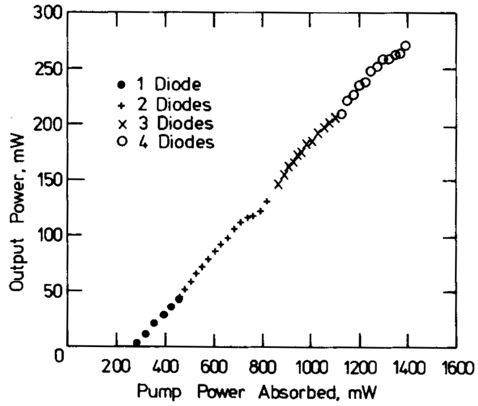

Fig. 7. Laser-diode-pumped Nd : glass laser performance with 15% output coupling.

a total incident pump power of 1.6 W. For pump powers greater than 1.6 W, the efficiency of the laser dropped off increasingly due to the limited power handling capability of the glass medium. Thermal damage (surface melting) was observed for powers in excess of 1 W incident on each surface. The optical slope efficiency of the laser was 36%. The fact that this shows only a slight improvement over the laser-diode-pumped performance indicates that the non-Gaussian output from the diode lasers is not seriously affecting the Nd : glass laser performance.

We also investigated the performance of the diode-laser-pumped laser when the laser output coupling was increased to 15%. This is of interest since as the output coupling is increased, the feedback from an external cavity will also increase, improving the chances of obtaining APM operation. The performance of the laser under these conditions is shown in Fig. 7. The laser threshold is increased to 260 mW, and the optical slope efficiency is 23.9%. The maximum output power obtained was 270 mW. Comparing these results to the work of Krausz *et al.* [8], it is apparent that this system provides a viable means of obtaining subpicosecond pulses from an all solid-state laser via self-starting APM operation. Preliminary results have recently been obtained from an APM laser-diode-pumped Nd : glass laser where the pulse duration was ~600 fs. This is the first demonstration of this source, and full details will be presented elsewhere.

IV. Single Frequency Operation

We have also investigated single frequency operation in the Ti : sapphire pumped Nd : glass laser. Several techniques have been developed to achieve single longitudinal mode operation from solid state lasers, including the use of short standing wave resonators [19] and intracavity etalons [20]. The use of ring lasers, where one of the two counter propagating traveling waves is suppressed, has also been widely reported, in particular the development of the nonplanar ring oscillator (NPRO) [21]. This suppression causes unidirectional oscillation and so overcomes spatial hole burning which would otherwise promote multimode oscillation. The approach taken in our experiment involved using a traveling wave acoustooptic modulator (Q switch) to introduce a differential loss between the counterpropagating beams in a ring laser. This technique was employed recently to obtain single frequency operation in a diode-pumped Nd : YAG laser [22], and has several advantages over the other techniques. In particular, much higher power operation can be obtained than from the very short, standing wave cavities, and the technique is simpler to implement than the NPRO. Also, the acoustooptic modulator can act as a Q switch if desired, and the technique can be used for those laser materials which do not have a large enough Verdet constant to achieve single frequency operation by applying a magnetic field to the laser material itself. Additionally, this method can be applied to laser materials exhibiting birefringence, such as Nd : YLF [23], since the unidirectional operation does not depend on polarization discrimination. The mechanism by which the modulator introduces differential loss between the two beams is not fully understood at present and requires further investigation.

The single frequency laser configuration is depicted in Fig. 8. This was arrived at by simply tilting the high reflector M_3 and output coupler in the standing wave configuration so as to complete the "figure-eight" ring path, and inserting an acoustooptic Q switch at the waist formed between these two mirrors. The Q switch was an AR coated plane surface lead molybdate device with an 80 MHz carrier frequency and a diffraction efficiency of about $0.3\ W^{1/2}$.

Unidirectional oscillation was achieved by tilting the modulator about 1° away from the Bragg diffraction angle where maximum diffraction efficiency occurs and applying 1 W of drive RF power. This provided sufficient differential loss to maintain single frequency operation up to 60 mW of laser output power. The corresponding pump power was 800 mW. It was noted that increasing the pump power above 800 mW required increasing the Q-switch diffraction power to prevent multimode operation. This acted to clamp the maximum power available in one beam. Furthermore, by increasing the diffraction power of the modulator, the cavity finesse was impaired, resulting in poorer gain extraction and subsequently a greater likelihood of thermal damage in the glass laser medium.

The linewidth of the laser was measured in a variety of ways. An optical spectrum analyzer (300 MHz free-spectral range confocal interferometer) indicated stable single frequency operation with the Q switch activated, with a mechanical frequency jitter of 8 MHz (not actively stabilized) and an instantaneous linewidth limited by the resolution of the analyzer at 2 MHz. A higher resolution measurement of the instantaneous linewidth was obtained using a homodyne scheme incorporating a 4.6 km fiber delay line. The measured linewidth of 60 ± 10 kHz yields a deconvolved linewidth of 32 ± 5.3 kHz. This was sufficiently close to the estimated resolution of 40 kHz, determined by the length of the delay line, that it has to be considered an upper limit on the laser linewidth [24].

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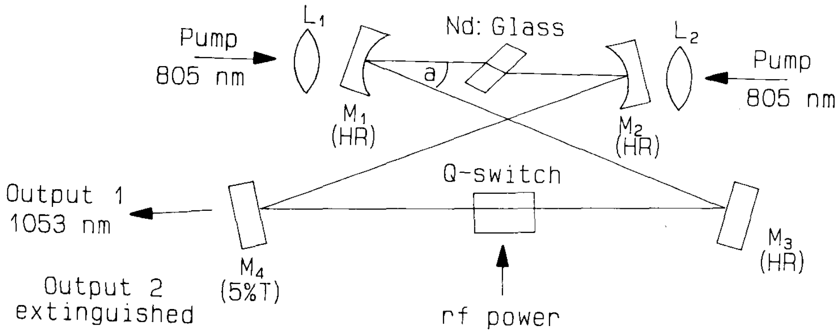

Fig. 8. Single frequency Nd : glass laser using an acoustooptic Q switch to force unidirectional oscillation.

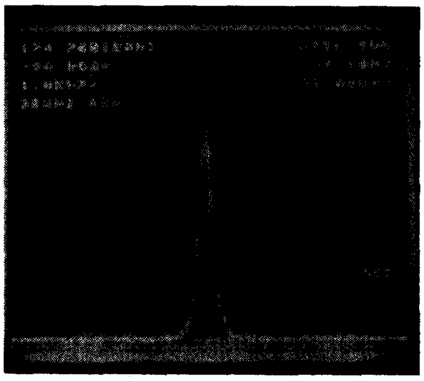

Fig. 9. Oscilloscope trace of intermode beat during dual mode operation. Deconvolution of the total signal bandwidth of 400 Hz indicates a single mode linewidth of around 150 Hz (scope resolution = 300 Hz).

To further improve the resolution of this measurement we have employed a novel technique based on dual mode oscillation. Dual mode oscillation (lasing on a pair of longitudinal modes of the laser resonator) was achieved with the laser running unidirectionally by misaligning the resonator slightly and reducing the RF power to the Q switch so that bidirectional (multimode) oscillation was just held off. Under these conditions, a pair of modes experiencing the same gain in the laser would oscillate until thermal drifting through the gain spectrum caused a jump to a different pair of modes. The two modes were not always adjacent in frequency, suggesting a shaping of the laser gain profile by residual etalon effects in the laser.

To measure the linewidth of an individual mode, the intermode beat was monitored with a fast photodiode and RF spectrum analyser at times when the two oscillating modes were adjacent. Deconvolving the beat signal (assuming a Gaussian frequency profile) gave a value for the longitudinal mode bandwidth and hence an upper limit on the linewidth of the laser when running single frequency (some broadening of the linewidth is expected due to the reduction in cavity finesse required to attain dual mode oscillation). Using this method, the instantaneous linewidth of the single frequency laser was found to be less than 200 Hz, the measurement being impaired by the 300 Hz minimum resolution of our RF spectrum analyzer. A plot of the intermode beat is shown in Fig. 9, indicating a total convolved signal bandwidth of 400 Hz, corresponding to an actual laser linewidth of around 150 Hz.

V. Summary

We have reported the active mode locking of a laser-diode-pumped Nd : glass laser. Using an acoustooptic amplitude modulator, a minimum pulse duration of 9 ps was obtained. The pulses were 1.6 times transform limited. In order to reach the powers necessary to make the laser-diode-pumped Nd : glass laser a viable source of sub-picosecond pulses via additive pulse mode locking, we have developed a high power (415 mW), high optical slope efficiency (32.4%) system. Four broad stripe laser diodes were used to pump the laser. The performance of this laser was similar to that obtained using a Ti : sapphire laser as the pump source. Using a Ti : sapphire laser to simulate pumping by laser diodes, we have demonstrated a single frequency Nd : glass laser. An acoustooptic modulator was used to enforce unidirectional operation of a Nd : glass ring laser. We have obtained up to 60 mW of single frequency output, and have measured the instantaneous linewidth of the laser to be less than 300 Hz.

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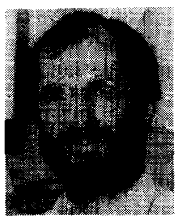

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