Mode locking of a diode-laser-pumped Nd:glass laser by frequency modulation

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We report frequency-modulation mode locking of a diode-laser-pumped Nd:glass laser. We have obtained pulses of 9-psec duration using a lithium niobate phase modulator operating at a repetition rate of 235 MHz. The average output power is 14 mW, for pumping with a 500-mW laser-diode array, and the pulses are approximately 1.4 times transform limited.

The neodymium-doped glass laser is a well-known source of short pulses owing to the large fluorescence linewidth ($\Delta\nu = 5.3$ THz)[1] of the lasing medium. The generation of short pulses from the Nd:glass laser has traditionally been achieved by the mode locking of flash-lamp-pumped pulsed systems. More recently[2-4] cw active mode-locked operation has been obtained by using an argon laser (operating at 514 nm) as the pump source. The development of diode-laser technology has led to the use of diode lasers as pump sources for actively mode-locked neodymium lasers.[5-11] The diode laser has several advantages over the argon laser for use as a pump source, in particular its higher efficiency and reduced associated thermal problems. Several authors[9-11] recently reported the performance of actively mode-locked, diode-laser-pumped Nd:glass lasers. The pulse durations obtained have ranged from 7 psec (Ref. 9) to 58 psec (Ref. 11).

The research reported to date on the active mode locking of laser-diode-pumped Nd:glass lasers has concentrated exclusively on the use of amplitude-modulation (AM) mode-locking techniques using an acousto-optic modulator. No research has been reported using electro-optic frequency-modulation (FM) mode locking, despite the fact that this technique has several advantages over acousto-optic techniques. For phase modulators, there is no need to adjust the angle of the crystal to optimize the Bragg angle. The operating frequency of a phase modulator can be changed without changing the modulator itself, which cannot be done for acousto-optic amplitude modulators. Also, electro-optic phase modulators show a broader resonance than acousto-optic amplitude modulators (typically several hundred kilohertz as opposed to several kilohertz). This means that FM mode-locked lasers will be less sensitive to thermal drift, which yields better long-term stability. A further advantage of FM mode locking is the negligible reduction in the average power of the laser when it is mode locked, compared with typically 10–30% reduction when AM mode locking is used. The use of FM mode-locking techniques is currently of great interest, as recent research[5,6] on AM and FM mode locking of a laser-diode-pumped Nd:YAG laser has shown that significantly shorter pulses could be obtained in the FM case (12 psec as opposed to 55 psec). The reason for this is not at present fully understood. It should be noted, however, that in these two references a cavity geometry different from ours was used, with the gain medium adjacent to the rear mirror. This geometry lead to a free-running laser bandwidth of 41 GHz, which is much broader than we have observed in our experiments, in which the gain medium was 20 mm away from the rear mirror. This broadening of the free-running laser bandwidth has been explained in terms of spatial hole burning.[12] In this Letter we report the operation of a laser-diode-pumped FM mode-locked bulk Nd:glass laser that yields pulses as short as 9 psec.

Figure 1 shows a schematic diagram of the FM mode-locked Nd:glass laser. The pump source was a 500-mW 10-stripe laser-diode array (Spectra-Diode SDL 2432) temperature tuned by a Peltier cooler to give optimum absorption (>90%) in the active medium [the Nd:glass laser has also been pumped with an STC LQ(P)05 broad-stripe (75-μm) laser diode, which yielded results similar to those reported here]. The diode beam was collimated by a compound lens (Melles Griot 06GLC001) of focal length 6.5 mm and numerical aperture 0.6 and passed through an anamorphic prism beam expander (magnification 5×). A 2× telescope was necessary in order to achieve single-

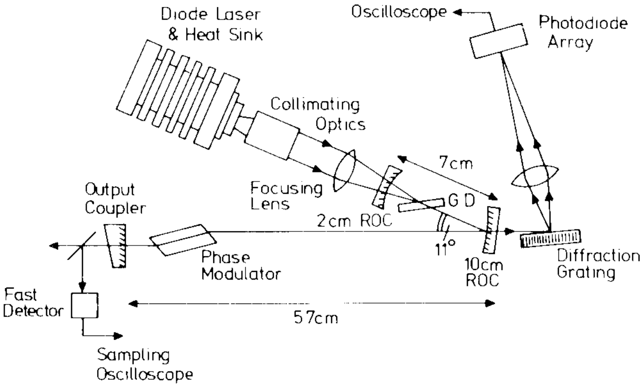

Fig. 1. Schematic diagram of the FM mode-locked Nd:glass laser. GD, LG760 glass disk.

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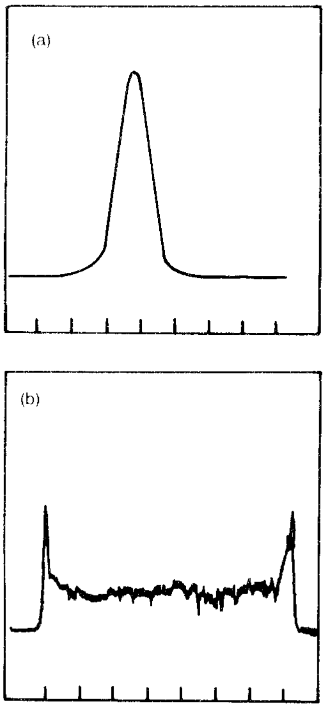

Fig. 2. (a) Free-running laser spectrum; scale, 7.5 GHz/division. (b) FM laser spectrum; scale, 75 GHz/division.

transverse-mode operation. The average spot size of the TEM$_{00}$ laser mode in the active medium was calculated to be $\langle\omega_0^2\rangle^{1/2} \approx 36$ μm, where the averaging was performed with the refractive index of the active medium taken into account. The diode beam was then focused through the cavity rear mirror [>99.9% reflectivity at 1.05 μm, >90% transmission at 800 nm, with a radius of curvature (ROC) of 2 cm] using a 3.2-cm focal-length lens. The cavity was completed by a 10-cm ROC turning mirror (>99.9% reflectivity at 1.05 μm) and a 10° wedged output coupler of reflectivity 98.5%. The angle of incidence on the curved mirror was 5.5°, which was the required angle to compensate for the astigmatism produced by the active medium.[13] The active medium was a 10-mm-diameter, 1.2-mm-thick disk of Schott LG760 phosphate glass, with an 8 wt. % Nd^{3+} concentration. The high dopant concentration was chosen to minimize the laser threshold. The disk was held between two copper plates to aid heat removal and was placed in the cavity at Brewster's angle.

Without the phase modulator in the cavity, the laser exhibited a threshold of 60-mW absorbed pump power with a slope efficiency of ≈9.5%. Cavity losses additional to the output coupling, such as reflections from the Brewster surfaces and leakage through the nominally highly reflecting mirrors, were measured to be approximately 0.25%. With the modulator in the cavity, the threshold increased to 170 mW. Since the laser threshold is directly proportional to the total cavity losses,[10] the passive insertion loss of the device was estimated to be 3%. The maximum cw power observed with the modulator in the cavity was 14 mW.

The phase modulator was a Brewster-angled LiNbO$_3$ crystal of dimensions 24 mm × 6 mm × 6 mm. The field was applied transverse to the modulator to make use of the largest electro-optic coefficient r_{33}. A rf of 235 MHz at a power of between 1 and 2 W was used to drive the crystal. A resonant circuit was formed by placing a coil (inductance approximately 70 nH) across the crystal (capacitance approximately 10 pF). The rf power was inductively coupled into this resonant circuit by using a second coil connected directly to the rf power amplifier. The dimensions of the electrodes used were 19 mm × 6 mm. The single-pass phase retardation of the device was measured by monitoring the Bessel-amplitude sidebands imposed on a He–Ne laser (λ = 632.8 nm) and was found to be greater than 1 rad per watt of rf power. At 1.05 μm the retardation was estimated to be 0.66 rad for a rf power of 1.5 W.

Mode-locked operation of the laser was readily achieved. Once the modulator resonance was found, the cavity length was adjusted until relaxation oscillations were observed. Two sets of relaxation oscillations exist, and satisfactory mode locking occurs over a frequency range of 2.5 kHz between these two regions. In an FM mode-locked laser there are generally two sets of pulse trains, owing to the existence of two phase extrema per rf period. These two trains could be clearly seen using a fast detector (GE Y-35-5252 25-GHz photodiode) and a Tektronix sampling scope. The measured pulse durations (FWHM) of the two trains were 90 and 50 psec. The shorter pulse train was observed over a larger portion of the 2.5-kHz frequency range than was the longer train. When the longer pulse train was observed, the shorter train could be selected by adjusting the modulator frequency by approximately 150 Hz. The shorter measured pulse duration was due to the limitation imposed by the combined response time of the fast detector and the sampling scope.

The spectral content of the laser output was monitored by using a 1800-lines/mm diffraction grating spectrometer. The free-running laser spectrum is shown in Fig. 2(a) and has a measured FWHM of 7.5 GHz (this value is approaching the resolution of our monitoring system, so the actual bandwidth may be less than this). As the modulator frequency was scanned through the 2.5-kHz mode-locking region, the pulse spectrum was observed to change shape, becoming at times multipeaked, and to shift in frequency. We have observed similar effects when this laser has been mode locked using an acousto-optic modulator.

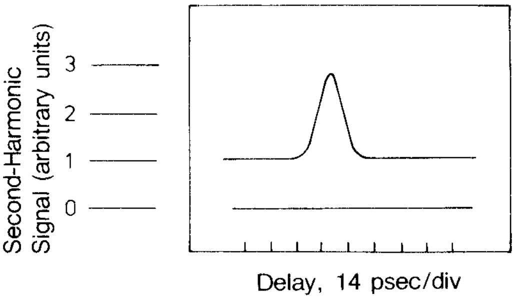

Fig. 3. Typical autocorrelation trace. An autocorrelation FWHM of 13 psec corresponds to an optical pulse FWHM of 9 psec, assuming a Gaussian temporal profile.

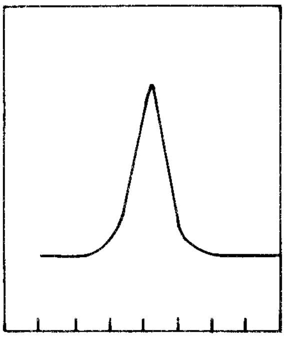

Fig. 4. Mode-locked laser spectrum; scale, 75 GHz/division.

On tuning the modulator frequency well away ($\approx$40 kHz) from the exact cavity repetition frequency on either side, the laser exhibited FM operation,[14] in which the laser output is constant but the instantaneous frequency sweeps sinusoidally over a large frequency range during each period of the modulator frequency. A typical spectrum of 530-GHz bandwidth observed when the laser was operating in this mode is shown in Fig. 2(b). The maximum bandwidth over which the laser has been observed to oscillate in this mode is $\approx$850 GHz. This mode of operation is currently under further investigation.

Accurate measurement of the pulse duration was carried out using a standard non-background-free autocorrelation technique. In our autocorrelator the moving prism was scanned at a rate of up to several hertz, and the scan range of the device was 98 psec. The second-harmonic generation signal produced by frequency doubling in a KTP crystal was detected with a photomultiplier tube. A typical autocorrelation trace of FWHM 13 psec is shown in Fig. 3. If we assume a Gaussian temporal profile, this corresponds to an optical pulse duration of 9 psec. The optical spectrum corresponding to this pulse is shown in Fig. 4 and has a FWHM of 70 GHz. A time–bandwidth product of 0.63 is thus obtained, which is 1.4 times transform limited. We have investigated the effect of varying the pump power, and hence the intracavity intensity, and found that there is no significant change in the pulse duration.

Authors working on both homogeneous (Nd:YAG)[6] and inhomogeneous (Nd:glass)[9] laser systems have reported significant reductions in the observed mode-locked pulse duration as compared with those predicted by the well-known Kuizenga–Siegman theory.[15] It has been argued that this may be due to self-phase modulation in the laser material. We compared our results with this theory and found no reduction (the calculated pulse duration was $\approx$4.5 psec). Since we also found no dependence of pulse duration on pump power, it would appear that no nonlinear effects are occurring in our laser.

In conclusion, we have reported FM mode-locked operation of a laser-diode-pumped Nd:glass laser. Pulse durations of 9 psec were obtained, at a repetition rate of 235 MHz. The average output power obtained was 14 mW, and the time–bandwidth product was 0.63. In principle it should be possible to compress these pulses to $\approx$6 psec by transmission through an optical fiber. We note that the laser is stable, and this is reflected by the fact that the autocorrelation traces are clean despite being acquired over 0.25 sec. We have also attempted to pump this laser using a 1-W laser-diode array but have encountered problems due to thermal damage in the glass disk. In order to scale this laser to higher powers it thus appears that an oscillator–amplifier system will be needed. Finally, we have observed that the FM mode-locked Nd:glass laser reported here did not give shorter pulses than have been obtained from AM mode-locked systems discussed elsewhere. This is not in agreement with the results obtained for a laser-diode pumped Nd:YAG laser reported in Refs. 5 and 6.

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