Application of optically compressed Nd: YAG laser pulses in synchronously pumped high-power dye lasers and the optically biased dye laser

A. S. L. GOMES, P. M. W. FRENCH, A. S. GOUEVIA-NETO†
and J. R. TAYLOR
Laser Optics Section, Physics Department, Imperial College,
Prince Consort Road, London SW7 2BZ, England

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Abstract. Temporally compressed pulses from a c.w. mode-locked Nd: YAG laser or Q-switched and mode-locked system have been used as the pump source for a novel optically biased synchronously excited dye laser and a high-power dye laser respectively. The former dye laser produced pulses of 1.5 ps and an average power of ~ 10 mW, while the latter generated 4 ps pulses with peak powers of 20 kW in an unoptimized cavity.

The optical pulse compression of mode-locked laser pulses [1] using the combined effects of self-phase modulation and group velocity dispersion in a single mode fibre, followed by a negatively dispersive delay line, which generally comprises a pair of diffraction gratings [2], has been shown to be a highly efficient and simple method for compressing femtosecond [3] and picosecond [4] pulses. Theoretical predictions [5] for compression on the single picosecond and femtosecond time scale have agreed excellently with experiment as regards required power levels, fibre length, compression ratio and grating separation. Compression has also been carried out for relatively long pulses [6-8], i.e. those in the 50-100 ps regime, and although theoretical prediction is not so precise in this case, especially for lasers operational around 1.1 μm, qualitative agreement is good.

Recently we have carried out an experimental investigation of the relevant parameters for the compression of the pulses from a c.w. mode-locked Nd: YAG laser [9]. In particular we examined the effect of the input power, fibre length, input pulse width and grating separation on the compression ratio achieved. As well as for the purely c.w. case, the compression of the Q-switched and mode-locked Nd: YAG was successfully carried out [10]. Consequently with a single-stage compressor in the purely c.w. condition it is possible to obtain average power levels of 1.2 W with pulse durations of 2.5 ps which corresponds to peak powers of 5 kW [9], while with a double-stage compression, pulses of 0.7 ps can be obtained with kilowatt peak powers [8]. Similarly a single stage with the Q-switched and mode-locked c.w. Nd: YAG yields 2.9 ps pulses of 1.5 MW peak power at repetition rates up to ~ 3 kHz [10]. Such power levels make the compressed laser output an attractive source for the synchronous excitation of other tunable laser sources, since it has been shown that the pulse width generated in a synchronously mode-locked laser is proportional to

† On leave from Departamento de Fisica, Universidade Federal de Alagoas, Maceio, 57000, AL, Brazil.
the square root of the pump pulse width [11]. In this article we report on the application of the two compressed pulse sources above, frequency-doubled and used as the master source in the synchronous pumping of a high-power pulsed dye laser and in an optically biased c.w. dye laser.

The synchronously pumped c.w. dye laser provides the simplest and most versatile source of tunable picosecond pulses [12]. However, the peak powers are typically ~ 100 W. Mode-locked and Q-switched solid state lasers have been used as the pump source using the fundamental [13] or the second harmonic [14] to excite dye laser sources giving pulses of the order of one megawatt. One disadvantage with this type of system is that the generated pulses tend to be relatively long, lying in the 20–35 ps range, this being a consequence of the long pump pulses. The optically compressed source of pulses is therefore very attractive since the high-power levels can be maintained while the pulse durations should be significantly reduced.

We have characterized the optically compressed Q-switched and mode-locked Nd : YAG laser previously [15] and a brief outline is sufficient here. The Q-switched and mode-locked Nd: YAG laser was operated in the prelase condition, which improves the pulse stability and reproducibility. Pulses of 85 ps duration were generated at 100 MHz repetition rate for Q-switch rates up to 3 kHz. For the work reported here a 1.2 kHz Q-switch cycle was used. An average power of 1 W from the laser was equivalent to a peak power of ~ 1 MW at the peak of the Q-switch envelope. A standard fibre-grating pair was used for the compression. The fibre was 90 cm long, single-mode, non-polarization preserving with a 7 µm core diameter, with 1 dB km⁻¹ loss at 1.06 µm and 35 ps nm⁻¹ km⁻¹ group velocity dispersion. The pair of 1800 lines/mm holographic gratings with 90 per cent diffraction efficiency at 75° angle of incidence were used in a double pass arrangement, which improves the beam quality [6, 9], with a total optical path of one metre. For this particular fibre length and grating separation the peak power in the fibre for optimum pulse compression was 100 kW (100 mW average power). After compression an average power of 30 mW was obtained. A standard second-harmonic generation autocorrelation technique was used to measure the average pulse duration throughout the compressed Q-switched pulse envelope, and a typical measurement is shown in figure 1, where a pulse of 3.7 ps was obtained (assuming Gaussian pulse shapes). This corresponded to a peak power of 800 kW, representing a 23 times reduction in the pulse duration and a four times increase in the overall peak power (only 200 kW peak power incident on fibre). No further increase in the peak power was possible as the power density was at the level of the damage threshold for SiO₂ fibre [16]. The second harmonic was generated by focusing the compressed pulses into a 5 mm long crystal of potassium titanate phosphate, KTiOPO₄ (KTP), using a 5 cm focal length lens. Peak powers of ~ 150 kW were obtained at 530 nm in pulse trains similar to that shown in figure 2 (a).

A simple four-mirror folded cavity arrangement was used for the dye laser cavity with tuning achieved using an intracavity prism. The pump radiation was coupled into the cavity via a 3 mm hole in the plane 100 per cent reflecting cavity end mirror and was focused into the 100 µm thick ethylene glycol jet of dye solution which was placed at the common focus of two 10 cm radius of curvature mirrors. Over the spectral range examined, the output mirror had a varying reflectivity, 5–20 per cent, and no attempt was made to optimize this component parameter. A differential micrometer permitted micron matching of the dye laser cavity to that of the pump laser. Figure 2 (b) shows a typical output train obtained with rhodamine 6G.
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Without any optimization 15 kW peak power was obtained at 575 nm, representing a conversion efficiency of 10 per cent. Matching of the cavity length in the pulsed regime was much less critical than the 1 μm accuracy required with c.w. synchronously pumped lasers and average pulse durations of 4-5 ps were obtained. A typical autocorrelation of the dye laser output at 570 nm is shown in figure 3. This trace is indicative of a pulse which consists of a burst of noise 4-7 ps wide with internal structure. As the pulses form within 30–40 round trips from an initial noise burst, such a pulse structure would be expected. It has been shown that input pulse to pulse variations in duration and amplitude in an autocorrelation can lead to determined pulse widths substantially shorter than the actual average pulse width due to the shorter more intense pulses giving a weighted enhancement to the nonlinear measurement process [17]. The measured pulse width of figure 3 illustrates this with the autocorrelation averaging over ~10⁴ pulses, varying from where broad noise bursts exist at the beginning of the train (giving rise to the broad wings of the autocorrelation) to the more complete formed pulses to the rear for property matched cavities. We have undertaken a study of the pulse formation mechanism throughout the mode-locked dye laser train, using a circularly scanning streak camera [18] operating in stroboscopic mode [19] and we have resolved on a picosecond time scale, the clear variation of pulse widths through the train from initial long noise bursts [20]. The advantage of the streak camera measurement technique to that of the autocorrelation method is that individual pulses can be recorded in a single shot. However, individual pulses of the mode-locked train can be observed with the autocorrelation technique using a box car integrator. This method can be widely applied and it should be possible to obtain frequency tunable picosecond pulses from 550 nm–1.5 μm and with optimization at peak power levels 50 kW or higher. Figure 4 shows typical tuning ranges and power levels obtained with this system for three different active dyes. By mixing the compressed fundamental and second harmonic, adequate power should be obtained at the third harmonic to provide a substantial pump source at 355 nm, and should add further to the versatility of the frequency-doubled compressed Q-switched and mode-locked
Nd:YAG laser as a pump source for high-power picosecond tunable lasers. For many applications however, a continuous source of high repetition rate picosecond pulses is desirable. Lower power levels can be tolerated since signal averaging techniques can enhance the detected information. The most versatile of sources is the synchronously pumped c.w. dye laser where generally a high-power acousto-optically mode-locked laser source is used to excite the dye laser. Typically the peak power in the pump source is \( \sim 100 \) W, at an average power level of \( \sim 1 \) W. Here we report on the use of a versatile method of producing tunable picosecond laser radiation with a synchronous pumping source derived from a frequency-doubled temporally compressed Nd:YAG laser, with peak powers similar to those above, but at average power levels of only 50 mW. The technique is the optical analogue of the electrical modulation of the gain first used to mode lock the semiconductor laser [21]. In that, a d.c. current is supplied to bias the semiconductor laser just below its lasing threshold, and an r.f. signal is applied on top of this which synchronously modulates the gain at the cavity round trip time. In the method described here an argon ion laser was used as the d.c. drive of the gain of a rhodamine 6G dye laser while the
frequency-doubled temporally compressed mode-locked Nd:YAG radiation gave rise to the synchronously pumped gain modulation. A schematic of the experimental arrangement is shown in figure 5. The 85 ps output pulses from a c.w. mode-locked Nd: YAG laser with an average power of 6 W were compressed in the usual manner using 60 m of the single-mode fibre described above and a pair of 1800 lines/mm holographic gratings separated by 1 m. The 3 ps pulses with an average power of 1.2 W were frequency-doubled in the 5 mm long KTP crystal giving an average power of ~60 mW in pulses 2 ps long at 530 nm. A spectra physics model 2020
Argon ion laser was directed via mirror $M_6$ and focused into the free flowing ethylene-glycol jet stream of rhodamine 6G off the broad band cavity mirror $M_3$. A standard four-mirror folded cavity configuration was used, with tuning achieved using a Brewster angled prism $P$; while the rear mirror $M_5$ was mounted on a differential micrometer translation stage to allow the micron accuracy needed in matching the dye laser cavity length to that of the 100 MHz mode-locked Nd: YAG laser. An average power level of $\sim 400 \text{ mW}$ was used from the argon ion which maintained the dye laser just below threshold. The frequency-doubled temporally compressed laser radiation was then directed into the jet via mirror $M_1$ and focused on top of the argon ion c.w. excitation region using mirror $M_2$. Laser threshold was achieved for only a few milliwatts of mode-locked pump power, and the frequency tunable output was monitored on an autocorrelator, and optimized by adjusting the cavity length. Typically an average power of $\sim 10 \text{ mW}$ was obtained with pulses as short as those of $1.5 \text{ ps}$ as shown in figure 6 being measured. This technique presents a versatile method of obtaining frequency-tunable picosecond mode-locked laser radiation and although demonstrated here for the standard rhodamine 6G system, the strength of the method will be to generate alternative wavelengths. This is particularly so in the blue spectral region where power levels of frequency-tripled temporally compressed radiation are not adequate to achieve synchronous pumping and laser threshold alone, and should allow the generation of picosecond pulses from 400 nm upwards.

In conclusion, we have demonstrated the versatility of the temporally compressed Nd: YAG laser as a pump for the generation of picosecond c.w. sources of radiation as well as high-power operation from the $Q$-switched and mode-locked synchronously pumped laser. These variable power levels, with the potentially wide spectral tuning should make the system ideal for many applications in photochemistry [22], nonlinear optics and optical fibre studies.

![Figure 5. Schematic of experimental arrangement used for the optically biased c.w. picosecond dye laser.](image-url)
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