HIGH ENERGY AND TUNABLE PICOSECOND LASER PULSES AT 1 kHz: SYNCHRONOUSLY PUMPING A DYE LASER WITH A MODE-LOCKED, Q-SWITCHED AND CAVITY DUMPED Nd:YAG LASER SYSTEM

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Efficient operation of a mode-locked, Q-switched and cavity dumped YAG laser and a synchronously pumped dye laser is described. Stable operation is observed up to repetition rates of 1.3 kHz. Introduction of the cavity dumping optics into the YAG oscillator results in only a modest decrease in the energy of the output pulse train, the operation of the dye laser is unaffected. At a 1.0 kHz repetition rate, cavity dumping the YAG oscillator immediately following cavity dumping the dye laser at the maximum of its gain results in a single pulse energies in excess of 0.6 mJ. Efficient second harmonic generation using CD*A produces pulse energies of 0.25 mJ (± 5% stability) with a pulse width of 80 ps. In addition, the second harmonic of the cavity dumped YAG can be used to amplify the output of the dye laser. Amplification to 20 μJ/pulse is observed for input energies ranging from 0.1 μJ/pulse to 10 μJ/pulse.

1. Introduction

For a large number of picosecond time resolved spectroscopic experiments, one requires high intensity pulses to initiate the photochemical or photophysical process of interest and a tunable laser pulse to probe the ensuing dynamics [1]. These desires have led to the design of a large variety of light sources. In most cases, low energy picosecond pulses are produced and the peak power is increased through a variety of amplification techniques. The most popular design to date has involved amplification of synchronously pumped dye lasers (or CPM lasers) using nanosecond YAG lasers [2]. These systems provide high energy, tunable laser pulses at repetition rates of 10–30 Hz. In addition, the peak power of the amplified pulse results in efficient harmonic generation and the ability to generate a white light continuum. However, for a wide variety of spectroscopic applications, one would like to have both high energy and tunable laser pulses at higher repetition rates. In the past few years, a variety of approaches along these lines have been pursued [3–6]. Using coupled YAG (or YLF) cavities, regenerative amplification techniques have been used to produce high peak powers and short pulses at repetition rates up to 1.1 kHz [4]. Amplification of femtosecond pulses using these techniques results in sufficient energy for efficient continuum generation and other nonlinear processes. In addition, pulse compression techniques coupled to the regenerative amplification have produced GW peak powers in pulses as short as 1 ps [5]. Recently, Miller and co-workers reported on a mode-locked Q-switched and cavity dumped YAG laser system which could be operated at repetition rates up to 500 Hz [6]. These workers demonstrated that such a laser system could also be used to produce high energy picosecond pulses.

In this communication we describe how a mode-locked Q-switched and cavity dumped YAG laser can be used to simultaneously provide high energy picosecond pulses along with tunable laser pulses from synchronously pumped dye lasers. By proper choice of Pockels' cells and driver electronics, repetition rates up to 1 kHz are easily achieved with pulse energies that are essentially independent of the repetition rate. The pulse widths of the cavity dumped YAG

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oscillator are ≈80 ps with a peak power of 7.5 MW. These intense pulses exhibit efficient harmonic generation and can be frequency mixed with the dye laser output to extend the tuning range of the laser source. The dye laser pulses are ≈20 ps with a pulse energy of 20 μJ (peak of the R6G dye curve). Insertion of the cavity dumping optics into the YAG oscillator has no effect on the operation of the dye laser. This laser system is ideal for a large variety of spectroscopic applications. The timing between the cavity dumped YAG pulse and the dye laser pulse is controlled by adjusting the timing between the two trigger pulses to the Pockels' cell driver electronics. In this manner, time resolved data on the hundreds of nanosecond time scale is easily obtained, requiring an adjustable optical delay which is equal to the interpulse separation in the Q-switch pulse envelope (≈10 ns). In addition the cavity dumped output of the YAG laser can be used to amplify the dye laser output.

2. Experimental

A schematic of the laser system is shown in fig. 1. The oscillator consists of a Quantronix Model 116 CW Nd:YAG laser which is acousto-optically mode locked at 50 MHz (Interaction Corporation Model ML-50Q), and acousto-optically Q-switched at an adjustable repetition rate up to 1.3 kHz (Interaction Corporation Model AQS-244A). The cavity mirrors are the standard mirrors supplied by Quantronix for a 50 MHz mode-locked laser system. The prelasing level is adjusted by the RF power to the Q-switch so that the first prelasing pulse is 400 μs behind the previous Q-switch pulse. Less prelasing level increases the power output at the sacrifice of pulse width and stability. Cavity dumping of the oscillator is achieved using a lithium niobate ($LiNbO_4$) transverse Pockels' cell (Interactive Radiation Model 204-080) and a dielectric polarizer (CVI). $LiNbO_4$ was chosen over KD*P due to higher repetition rates attainable using this material and the higher damage threshold of its newly improved coating. We found protection of $LiNbO_4$ by beam expanding is not necessary. The electro-optic driver circuit is similar in design to that recently reported by Dlott and co-workers [7]. This design uses high voltage MOSFETs to switch the quarter wave voltage. The rise time of the circuit was found to be ≈6 ns. These devices offer superior performance (higher repetition rates and increased reliability) over the more conventional avalanche transistor chains. The circuit can be easily operated up to repetition rates of 5 kHz. Stable operation of the YAG laser is limited to ≈1.3 kHz.

The IR output from the YAG laser is focussed into a 3 mm×3 mm×8 mm piece of KTP (Airtron) using a 40 cm focal length lens which is positioned 25 cm away from the KTP; a 35% conversion to the second harmonic is obtained. This light is used to synchronously pump a tunable dye laser. The dye laser design is also given in fig. 1. Both cavity mirrors are flat broad band dye laser mirrors (Virgo). The 1 mm flowing dye cell sits between a 10 cm and 30 cm plano-convex glass lens. The spot size of the laser beam at the dye cell is ≈200 μm. For broad band

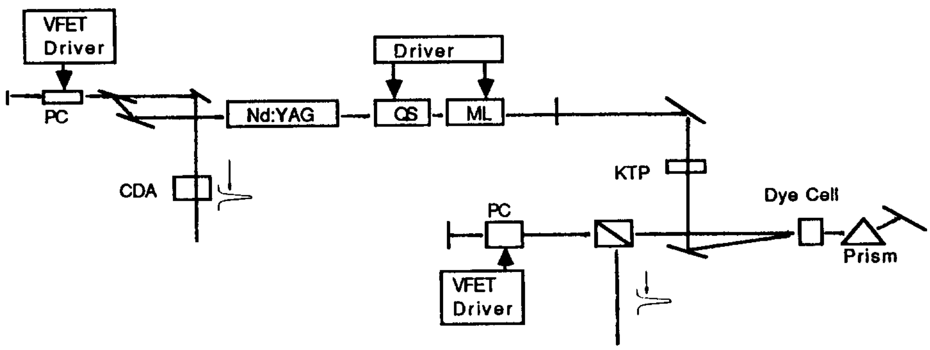

Fig. 1. A block diagram of the mode-locked, Q-switched and cavity dumped Nd:YAG laser and synchronously pumped dye laser. Abbreviations: PC: Pockels' cell, QS: acousto-optic Q-switch, ML: acousto-optic mode-locker.

tuning (spectral widths of ≈3 Å) a prism mirror combination is used. This provides easy tuning of the dye laser without walking the output beam. For narrow spectral widths, a pair of etalons are used. The dye laser is cavity dumped using a polarizer (Newport) KDP Pockels' cell (Quantum Technology) combination. The driver electronics are identical to that used to cavity dump the YAG oscillator.

Timing is controlled by a fourchannel delay generator (Stanford Research Systems, Model DG 535). This unit is triggered by a fast photodiode which monitors leakage through the rear mirror of the YAG oscillator. At adjustable delays form this trigger pulse, the YAG oscillator is cavity dumped after the dye laser pulses reach maximum energy.

Pulse widths were determined using a Streak Camera (Hamamatsu C979) Reticon (EGG Model 1420) detection system. The Reticon data is transferred to a LSI-11/23 computer system. The maximum repetition rate of the detection system is 22 Hz. In order to examine single pulses, the laser system was Q-switched at 1 kHz, but count down electronics were were used to cavity dump the YAG and dye lasers ever 100 shots, giving an effective cavity dumping rate of 10 Hz. Pulse energies were measured by cavity dumping the YAG at the Q-switch repetition rate of 1 kHz. The pulses were detected by a photomultiplier (1P28). The output of the PMT was processed by a track-and-hold circuit (Stanford Research Systems Model SR250), and fed into the A-D converter of a MassComp Lab Computer System (Model 5450).

3. Results and discussion

In a normal cavity-dumped dye laser which is synchronously-pumped by a Q-switch mode-locked YAG laser, the dye laser pulses reach a maximum at 5–6 pulses after the maximum pulse of the Q-switch envelope. Once the maximum dye laser pulse is cavity-dumped, the residual IR pulses do not affect the dye laser output. These pulses reflect the fact that there still is substantial energy in the YAG cavity after the dye laser is cavity dumped. One approach which is commonly used to take advantage of this "spare" energy is to use a double Pockels' cell external to the YAG cavity to extract a single pulse from the residual pulse train. Considering that these pulses come from the single pulse traveling inside the cavity, one can make full use of this extra energy by intracavity dumping the YAG immediately after the dye laser is cavity-dumped. Mode-locked, Q-switched, and cavity dumped YAG lasers (the all in one) have been developed and found to generate high energy pulses [3,6]. In our system, a 12% output coupler is used. By optimizing the resonator condition and electrooptical switching, we are able to pump a dye laser and simultaneously provide high energy IR pulses. This hybrid design is characterized not only by its high energy and high repetition rate but also by its simplicity, reliability and low cost.

The insertion of intracavity polarizers into a YAG cavity generally results in a loss of power due to the thermal birefringence of the laser rod. In a previous report by Miller et al. [6], insertion of a pair of intracavity polarizers into a mode-locked Q-switched Nd:YAG resonator had a significant effect on the power and the current needed to provide maximum output. Our design incorporates one high efficiency dielectric polarizer and a high reflector in place of a second polarizer. We find that this combination does not dramatically affect the operation of the YAG laser. However, the insertion of a $LiNbO_4$ Pockels' cell does result in a 30% loss of energy. The energy per Q-switch pulse reduces from 2 mJ to 1.4 mJ. Maximum outputs with and without the cavity dumping optics are both observed at 32 A pumping current. The location of the laser head in the cavity is also unchanged.

Second harmonic generation of this Q-switched mode-locked IR pulse train produces 450 mJ of 532 nm light per Q-switch burst. This light serves as the pump beam for the dye laser. Cavity-dumping of the YAG oscillator reduces the 532 nm energy by ≈1/3 to 1/2. However, this has no effect on the dye laser performances as the portion of the mode-locked Q-switched output that pumps the dye is unaffected by cavity dumping the oscillator. In fact, the cavity dumping helps to eliminate the satellite pulses following the dye laser output pulses which result from inefficient dye laser cavity dumping. When all the green light is used to pump a R6G dye laser, we obtain 22 μJ of dye laser output at 570 nm. By splitting the green light into two equal intensity beams, we are able to pump two dye lasers. The two dye lasers are quite stable, each having an output of 7–9 μJ.

The cavity dumped IR has a pulse energy of 0.6 mJ, repetition rate of 1 kHz and pulse width of 80 ps fwhw. The streak camera trace of its second harmonic is shown on fig. 2A along with that of dye laser output, fig. 2B. The efficiency of YAG cavity dumping is greater than 90%. After the second harmonic generation the satellite pulses are hardly noticeable. The stability of the frequency doubled light is extremely good as demonstrated in fig. 3. The full width at half maximum is less than 10%. This IR output is a versatile source which can find numerous applications in conjunction with the dye laser output.

Using a 4 cm CD*A doubling crystal, we obtain second harmonic pulse energies of ≈0.25 mJ. Efficient third and fourth harmonic generation are also observed. If a dye laser is not needed, the 12% output coupler can be replaced by a high reflector in order to obtain more energy in the cavity dumped pulse. Replacing the YAG crystal by YLF offers to be a promising source for higher output energies and shorter pulse width (40 ps). The intense cavity dumped IR beam can also be used for frequency mixing with the dye laser output extending the tuning range of the laser system.

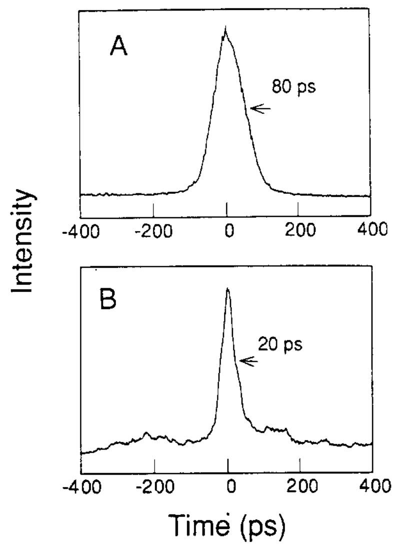

Fig. 2. Streak camera traces of (A) frequency doubled output of the cavity dumped YAG oscillator and (B) a cavity dumped dye laser at 570 nm (Rhodamine-6G).

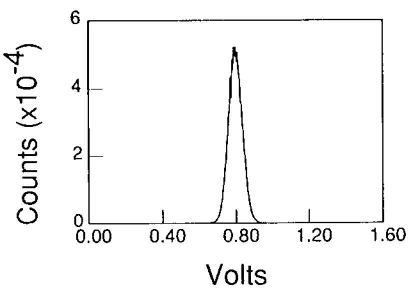

Fig. 3. Histogram of the energy of the frequency doubled output of the cavity dumped YAG oscillator. One milliion pulses were examined. The full width at half maximum is ≈10%.

The pulse width (20 ps) of the synchronously pumped cavity dumped dye laser (fig. 2B) is longer than that of a normal synchronously pumped dye laser, resulting from the limited round trips in the dye laser cavity [8]. However, with the recent advances in fiber optic compression techniques [9], the dye laser output could be compressed to ≈1–2 ps. The damage threshold of most fiber optics limits the input energy; as a result, the output energy of the compressed pulse is substantially less than the dye laser output. We have found that by using the second harmonic of the cavity dumped YAG pulses to pump a R6G dye amplifier cell, dye laser pulses of 15–20 μJ/pulse can be generated for input pulse energies ranging from 100 nJ to 10 μJ. Thus, it should be possible to amplify the compressed output back up to ≈10 μJ/pulse. We are currently exploring this design and will report the results at a later date. The advantages of this scheme over other amplified synchronously pumped dye lasers would be the ease of operation and low cost.

4. Concluding remarks

We have described a YAG laser system which using one resonator can deliver high energy (0.6 mJ/pulse) IR pulses at high repetition rate (1 kHz) and synchronously pump a dye laser. Both the YAG and dye laser outputs are stable (±5% peak-to-peak). The efficient extraction of the YAG cavity pulse provides, at low cost, a light source which can be used for both nonlinear frequency mixing and picosecond pulse amplification. This system will prove useful for a variety of spectroscopic applications requiring high peak power and high repetition rate.

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References

[1] G.R. Fleming, Chemical applications of ultrafast spectroscopy (Oxford University Press, New York, 1986).

[2] T.L. Koch, L.C. Chiu and A. Yariv, J. Appl. Phys. 53 (1982) 6047;
R.L. Fork, C.V. Shank, R. Yen and C.A. Hirlimann, IEEE J. Quant. Electron. QE19 (1983) 500;
G. Maneke, J. Schroeder, J. Troe and F. Voss, Ber. Buns. Phys. Chem. 89 (1985) 896.

[3] D.B. McDonald and C.D. Jonah, Rev. Sci. Inst. 55 (1984) 1166;
D.H. Waldeck, W.T. Lotshaw, D.B. McDonald and G.R. Fleming, Chem. Phys. Let. 88 (1982) 297;
T.L. Gustafson and D.M. Roberts, Optics Comm. 43 (1982) 141;
M.A. Kahlow, W. Jarzeba, T.P. DuBruil and P.F. Barbara, Rev. Sci. Inst., submitted for publication;
J.B. Hopkins and P.M. Rentzepis, Appl. Phys. Lett. 47 (1985) 777;
W.H. Knox, M.C. Downer, R.L. Fork and C.V. Shank, Optics Lett. 9 (1984) 552.

[4] T. Sizer and I.N. Duling III, IEEE J. Quant. Electron. QE24 (1988) 404;
T. Sizer II, J.D. Kafka, I.N. Duling III, C.W. Gabel and G.A. Mourou, IEEE J. Quant. Electron. QE19 (1983) 506;
P. Bado, M. Bouvier and J.S. Coe, Optics Lett. 12 (1987) 319;
I.N. Duling III, T. Norris, T. Sizer II, P. Bado and G.A. Mourou, J. Opt. Soc. Am. B 2 (1985) 616.

[5] J.S. Coe, P. Maine and P. Bado, Regenerative amplification of picosecond pulses in Nd:YLF: effect of gain narrowing and gain saturation, Optics Lett., submitted for publication.

[6] R.J.D. Miller, L. Min and M.A. Shragowitz, Optics Comm. 62 (1987) 185.

[7] J.C. Postlewaite, J.B. Miers, C.C. Reiner and D. Dlott, IEEE J. Quant. Electron. QE-24 (1988) 411.

[8] F. Patterson, Ph.D. Thesis, Stanford University, 1986.

[9] D. Grischkowsky and A.C. Balant, Appl. Phys. Lett. 41 (1982) 1;
B. Nikolaus and D. Grischkowsky, Appl. Phys. Lett. 42 (1983) 1;
B. Nikolaus and D. Grischkowsky, Appl. Phys. Lett. 43 (1983) 228.