1 April 1997

ELSEVIER

Optics Communications 136 (1997) 433–436

OPTICS COMMUNICATIONS

Picosecond Nd:YLF laser–multipass amplifier source pumped by pulsed diodes for the operation of powerful OPOs

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Received 24 September 1996; accepted 14 November 1996

Abstract

Picosecond pulse trains from a quasi cw Nd:YLF oscillator are amplified by a multipass system pumped by a pulsed 100 W peak power laser diode. Gain factors in the order of 100 are achieved with input pulses of 100 nJ energy and 2 ps duration. The high power of the amplified pulse trains allows the operation of a quasi-cw synchronously pumped KTP optical parametric oscillator (OPO) at high output coupling. Pumping by the second harmonic provides OPO pulses of 2.1 ps duration in trains consisting of 25 pulses with a noteworthy flat top of the envelope. The conversion efficiency of 13% corresponds to a total energy of 50 μJ in the trains. The parameters promise wide applications of the system in ultrafast spectroscopy.

Optical Parametric Oscillators (OPO) and Optical Parametric Generators (OPG) are becoming well established and widely used coherent sources of picosecond and femtosecond light pulses tunable in the visible and IR wavelength region [1]. Nevertheless, there are new problems arising with the advent of diode-pumped picosecond solid-state lasers.

The high stability and brightness of such lasers motivated numerous research efforts on holosteric (all-solid-state) synchronously pumped laser–OPO systems starting in 1990 with mode-locked and *Q*-switched laser sources [2]. They generate pulses with strongly varying parameters throughout the OPO output train. Continuous pulse trains of high stability are emitted from cw picosecond OPOs. Development of holosteric cw modelocked systems begun in 1992. Their typical output parameters are pulse widths in the order of a few ps and energies up to 1 nJ [3]. Because of the low output peak power applications of such OPOs in ultrafast spectroscopy particularly in pump- and probe-experiments have been very limited.

Higher output powers are achieved by increasing the average power of cw diode-pumped picosecond lasers [4]. However, in cw operation strong thermal loading is an obstacle difficult to overcome in attaining average powers on the level of several watt. Moreover, there are many spectroscopic experiments where high average power is unfavorable but high peak power is preferred. These problems can be overcome by quasi-cw multipass amplifiers. Such systems pumped by cw diodes have been realized for cw and ns-lasers [5,6] and for ps-lasers with moderate output powers [7].

To this end we have elaborated a new approach to our best knowledge not used before and based on a solid-state laser [8] and multipass amplifier system pumped by quasi-cw diodes of 100 W peak power. This approach generates short trains of picosecond pulses with a nearly flat envelope in contrast to *Q*-switched laser sources [2] and single pulse energies 5×10^2 times higher than quasi-cw amplifiers pumped by cw diodes [7].

To demonstrate the potential of such a system the output was frequency doubled and was used to drive a synchronously pumped KTP [9] OPO built up in a linear folded geometry. Pumping by these intense pulses makes alignment of an OPO very easy and enables us to boost the single pulse output energy of an OPO to 200 nJ at 2.1 ps

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PII S0030-4018(96)00733-X

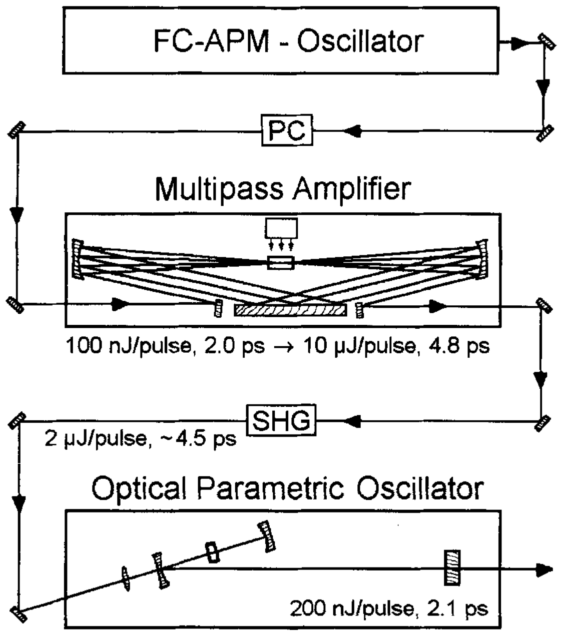

Fig. 1. Schematic of the pulsed, holosteric, synchronously pumped laser–OPO system. The optical parametric oscillator with a linear folded cavity is pumped by an additive-pulse mode-locked (FC-APM) Nd:YLF oscillator/multipass amplifier arrangement. PC: Pockels cell for selecting the number of pulses in a pulse train; SHG: KTP crystal for frequency doubling.

pulse duration. We demonstrate optical parametric oscillation with output parameters very suitable for ultrafast spectroscopy and nonlinear optics.

The scheme of the laser system is depicted in Fig. 1. Trains of several hundreds of individual pulses are generated in an additive-pulse mode-locked, amplitude-controlled (FC-APM) Nd:YLF oscillator [10] pumped by quasi-cw laser diodes at a 30 Hz repetition rate [5]. At its output coupler stable trains of ~ 400 pulses (repetition rate of 100 MHz) of 150 nJ energy and 2.0 ps duration are available. They are fed through a Pockels cell (PC), which selects a train consisting of an adjustable number of individual pulses.

The selected pulse train is injected into a three-mirror ring multipass amplifier similar to that in Ref. [11]. It consists of two dielectric mirrors (radius of curvature 50 cm) and a flat gold-coated mirror of 11 cm length. The two curved mirrors are separated by the sum of their focal lengths (50 cm). The amplifier medium located in the focal position of the mirrors is a π-cut Nd:YLF slab [2 mm (height) × 5 mm (width) × 15 mm (length)] doped with 1 at.% Nd.

The slab is pumped by a single 100 W thermoelectrically cooled pulsed diode laser bar (Spectra Diode Labs SDL-3251-A1). Its emission is temperature tuned to meet the absorption peak of the laser medium at 797 nm. A half-wave plate is placed between the diode and the crystal in order to utilize the larger absorption of pump light polarized parallel to the Nd:YLF c-axis [12]. The pump light is focused into the crystal with the help of a microlens [13]. Approximately 90% of the 40 mJ pump pulse energy is absorbed in the crystal. The maximum small signal gain per transit is measured to be 2.5. The beam diameter in the crystal is ~ 180 μm (FWHM).

The input energy of 100 nJ per pulse is boosted in 8 transits by about two orders of magnitude to the 10 μJ regime. Amplifying a block of 150 individual pulses, the total energy extracted is ~ 1 mJ with a high short term reproducibility of ~ 2%. In this situation the optical efficiency of the amplifier is 2.5%.

At maximum total amplification, the envelope of the pulse train is influenced by gain saturation. The pulse amplitude drops by a factor of 2 within 100 amplified pulses. An increase of the pulse duration to 4.8 ps by the amplification process is measured. These observations nicely compare with numerical estimates on gain satura-

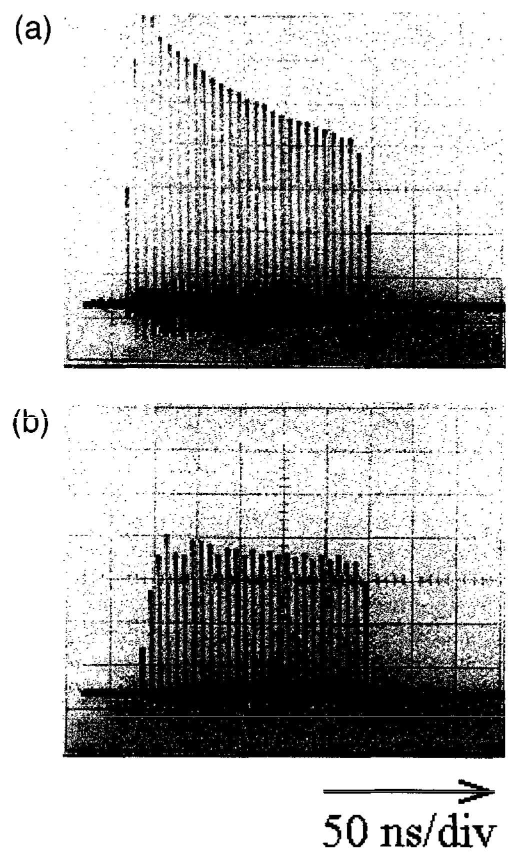

Fig. 2. Oscilloscope traces of (a) the pump pulse train at the second harmonic of the Nd:YLF laser and (b) the OPO output pulse train. The time scales are 50 ns/division. The pump pulse train consists of ~ 25 pulses. The pulse energy in (a) drops on account of gain saturation in the amplifier.

tion and gain narrowing. E.g., a rise of the pulse duration to 4.1 ps is predicted by the calculations.

The amplified pulse trains are frequency doubled by a KTP crystal (SHG in Fig. 1) with a conversion efficiency of 20%. As an example, a pulse train consisting of 27 pulses is depicted in Fig. 2a. Here we observe a more pronounced decrease of the energy along the train which is explained by a drop of second harmonic conversion efficiency with decreasing intensity. The SH pulse duration is calculated to ~ 4.5 ps. The average energy of a single second harmonic pulse is ~ 2 μJ. M^2 is measured to be 1.12.

The second harmonic pulses are applied to synchronously pump an OPO in linear folded resonator geometry (see Fig. 1). It consists of a KTP crystal (type II phase matching, $l = 7$ mm, $\theta = 90°$, $\varphi = 25°$), two HR spherical mirrors ($r = 35$ cm) and a plane output coupler ($T = 20\%$) mounted on an adjustable translation stage. The SH radiation is focused into the nonlinear crystal, which is placed in the focal plane of the two curved mirrors. The peak intensity of the pump beam in the crystal is ~ 0.45 GW/cm^2, which is high enough to produce observable parametric fluorescence.

Tunability of the OPO was out of our concern and was limited to the range of 1044–1050 nm by the angular aperture of the nonlinear crystal. The output parameters are measured to be as follows: pulse duration 2.1 ps (averaged along the train), time–bandwidth product $t_p \times \Delta\tilde{\nu} = 0.4$ and a total conversion efficiency of 13% corresponding to a single pulse energy of ~ 200 nJ. We did not observe any significant pulse shortening effects [14] what is consistent with numerical simulations for this type of KTP OPO in the high gain regime.

Fig. 2b shows the pulse train generated by the OPO. A comparison with the pump pulse train in Fig. 2a shows two interesting features: (i) The lengths of the pulse trains are the same within two pulses. Obviously the build-up time of OPO emission is very short which is expected for a high gain system. (ii) The envelope of the OPO output pulse train shows a nearly flat top. Simultaneously the depletion of the pump pulses at the beginning of the train is more pronounced similarly to observations in modelocked Q-switched systems [15] and the residual pump pulse train shows also a flattened envelope. The reason for these flat top envelopes is not completely understood at the moment. Nonlinear losses in the KTP crystal or gain dynamics under the presence of a decreasing pump intensity may result in the observed behavior.

Fig. 3 shows the dependence of the energy conversion on the cavity length detuning of the OPO at degeneracy. Nearly constant output energy is observed while varying the cavity length by 800 μm. Such a large tolerance of the cavity length is typical for an OPO operated far above threshold. The maximum mismatch per round-trip approximately corresponds to a separation of the pump pulse and the OPO pulse of the order of a pulse duration. The findings are in qualitative agreement with the results derived from numerical simulations at a pump intensity of 0.45 GW/cm^2 (see dashed line in Fig. 3). However, a profile of the theoretical curve features a pronounced modulation which we did not observe in the experiment. We attribute this to the plane wave approximation used in

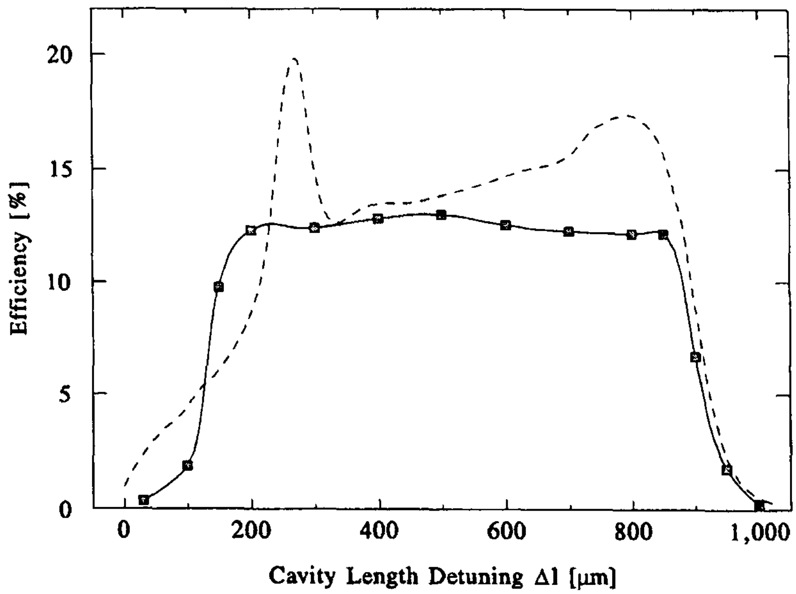

Fig. 3. Energy conversion efficiency versus cavity length detuning of the optical parametric oscillator. The intensity of the pump pulses was $I_{pump} \approx 0.45$ GW/cm^2. The nearly constant conversion efficiency within a cavity detuning of $\Delta l \approx 800$ μm indicates strong saturation of the OPO. The dashed line represents numerical simulations with $I_{pump} = 0.45$ GW/cm^2.

the numerical simulation. The Gaussian transversal profile of the beam and the beam walk-off produce the total flattening of the cavity detuning curve observed experimentally.

In conclusion, we have demonstrated a Nd:YLF diode-pumped multipass amplifier which boosts the single pulse energy of pulse trains by two orders of magnitude from 100 nJ to 10 μJ. Input pulses from quasi-cw or cw diode pumped Nd:YLF lasers can be applied. A KTP OPO has been synchronously pumped by the trains of this new pump source after frequency doubling. The approach provided an OPO output energy of 200 nJ/pulse in flat-top trains of a total energy reaching 5 μJ. It should be mentioned that due to the high power of the pump pulses an alignment of parametric oscillator is straightforward and the OPO operates even with high cavity losses.

Acknowledgements

A.P. thanks the Graduiertenkolleg "Nichtlineare Spektroskopie und Dynamik" at the University of Bayreuth for supporting the participation in this research project. The authors acknowledge numerical simulation data provided by G. Valiulis.

References

[1] For a review, see: R.L. Byer and A. Piskarskas, eds., Special issue on Optical Parametric Oscillation and Amplification, J. Opt. Soc. Am. B 10 (1993) 1656–1764; 2148–2243; W.R. Bosenberg and R.C. Eckardt, eds., Special issue on Optical Parametric Devices, J. Opt. Soc. Am. B 12 (1995) 2084–2320.

[2] G.T. Maker and A.I. Ferguson, Appl. Phys. Lett. 56 (1990) 1614; M. Ebrahimzadeh, G.J. Hall and A.I. Ferguson, Optics Lett. 16 (1991) 1744.

[3] M. Ebrahimzadeh, G.P.A. Malcolm and A.I. Ferguson, Optics Lett. 17 (1992) 183; M.J. McCarthy and D.C. Hanna, Optics Lett. 17 (1992) 402; A. Robertson and A.I. Ferguson, Optics Lett. 19 (1994) 117; S.D. Butterworth, S. Girard and D.C. Hanna, J. Opt. Soc. Am. B 12 (1995) 2158.

[4] W.T. Lotshaw, J.R. Unternahrer, M.J. Kukla, C.I. Miyake and F.D. Braun, J. Opt. Soc. Am. B 10 (1993) 2191.

[5] H. Plaessmann, S.A. Ré, J.J. Alonis, D.L. Vecht and W.M. Grossman, Optics Lett. 18 (1993) 1420.

[6] W.R. Bosenberg, A. Drobshoff, D.C. Gerstenberger, L.E. Myers, R.C. Eckardt, M.M. Fejer and R.L. Byer, in: Proc. Advanced Solid State Lasers Conference 1995, paper PD8.

[7] S.D. Butterworth, W.A. Clarkson, N. Moore, G.J. Friel and D.C. Hanna, in: Proc. Advanced Solid State Lasers Conference 1996, paper WD7.

[8] P. Heinz and A. Seilmeier, Optics Lett. 21 (1996) 54.

[9] J.D. Bierlein and H. Vanherzeele, J. Opt. Soc. Am. B 6 (1989) 622.

[10] P. Heinz, A. Reuther and A. Laubereau, Optics Comm. 97 (1993) 35.

[11] S. Backus, J. Peatross, C.P. Huang, M.M. Murnane and H.C. Kapteyn, Optics Lett. 20 (1995) 2000.

[12] J.R. Ryan and R. Beach, J. Opt. Soc. Am. B 9 (1992) 1883.

[13] M.D. Selker, R.S. Afzal and P. Reichert, IEEE J. Quantum Electron. QE-30 (1994) 1616.

[14] A. Umbrasas, J.-C. Diels, J. Jacob and A. Piskarskas, Optics Lett. 19 (1994) 1753.

[15] G.J. Hall, M. Ebrahimzadeh, A. Robertson, G.P.A. Malcolm and A.I. Ferguson, J. Opt. Soc. Am. B 10 (1993) 2168.