Appl. Phys. B 76, 355–358 (2003)
DOI: 10.1007/s00340-003-1143-5

Applied Physics B
Lasers and Optics

W. ZENDZIAN✉
J.K. JABCZYŃSKI
J. KWIATKOWSKI

Intracavity optical parametric oscillator at 1572-nm wavelength pumped by passively Q-switched diode-pumped Nd:YAG laser

Institute of Optoelectronics, Military University of Technology, 2 Kaliskiego Str., 00-908 Warsaw, Poland

Received: 15 October 2002/Revised version: 19 February 2003

ABSTRACT An intracavity optical parametric oscillator (IOPO) based on bulk KTP crystal was constructed with a Nd:YAG slab as an active medium pumped by a 300-W diode array and Cr:YAG as a passive Q-switch. A signal pulse of 1.9-mJ energy at 1572-nm wavelength was demonstrated. In the cavity, optimized with respect to single-pulse energy, a five-fold shortening of signal-pulse duration with respect to 1064-nm pump radiation was observed. A twice as large level of signal peak power of 650 kW, compared to the pump laser in the same cavity without the IOPO, was achieved. A conversion efficiency of 44% with respect to the 1064-nm pump beam and 3.8% with respect to diode pump energy was demonstrated.

PACS 42.55.Xi; 42.60.Gd; 42.65.Yj

1 Introduction

High peak power ‘eye-safe’ lasers attract great interest in the laser market due to minimization of the risk of human-eyesight damage and excellent propagation properties in the atmosphere. Three types of ‘eye-safe’ lasers are of practical importance: lasers with erbium (Er)-doped media directly operated at 1.5–1.7 μm wavelength [1–6], Raman lasers pumped by pulsed neodymium (Nd) lasers operating at the strongest 1064-nm or 1340-nm lines [7–10], and optical parametric oscillators (OPOs) pumped by high peak power Nd lasers [11–29, 32]. These three types of lasers can be lamp or diode pumped. The main drawback of lamp-pumped Er lasers are their weak thermal properties limiting repetition rates to a few Hz. The efficient pulsed Er:glass lasers were demonstrated for diode pumping [4–6], but until now with relatively low peak power. Raman lasers operating at third Stokes’ shift starting from 1064 nm can satisfy such requirements [7, 8]; however, their optical efficiencies are low and threshold power densities exceed hundreds of $\mathrm{MW/cm^2}$. The efficiencies of Raman lasers based on the first Stokes’ shift starting from 1340 nm are considerably higher; however, both an efficient pump source at 1340 nm (with peak power $> 100\ \mathrm{MW/cm^2}$) and high-quality solid-state Raman crystals are not widespread and commercially available nowadays. However, near quantum limit efficiency of solid-state Raman lasers was demonstrated lately for picosecond pulsed pump beams (see e.g. [9]); thus such a type of ‘eye-safe’ source can be competitive in the near future.

In our opinion, nowadays the best approach for a pulsed ‘eye-safe’ laser is the application of an OPO pumped by a high peak power Nd laser. The main advantages of such a type of laser are:

- matured technology of pumping lasers,
- high efficiency approaching the quantum limit,
- possibility of precision tuning and control of signal wavelength,
- commercial availability of a wide range of non-linear crystals including periodically poled structures (see e.g. [16–19]),
- significantly lower threshold intensities compared to Raman lasers,
- high repetition rates or cw regime possible due to application of periodically poled crystals,
- compactness and relatively low thermal limitations compared to Er lasers.

Since the early 1970s, OPOs have been constructed employing lamp-pumped lasers. In the last decade, diode-pumped OPO lasers have attracted great interest of research laboratories and commercial companies [11–28]. For such a specific aim, two types of diode-pumped ‘eye-safe’ OPOs have been developed:

- a single resonant (external) OPO based on PPLN [20] or PPKTP [21],
- a single resonant internal OPO (IOPO) [24–29].

The idler beam is completely attenuated in both types; however, significantly higher non-linearity is required in the first case. In the second case, bulk non-linear crystals (typically KTP or $\mathrm{LiNbO_3}$) can be used in IOPO lasers because of much higher pump intensities. For an IOPO active or passive Q-switching can be applied for the pump laser. The cost-effective (but less efficient) solution is the application of solid-state passive Q-switches (mainly $\mathrm{Cr^{4+}}$:YAG) for a Nd-crystal

---

✉ Fax: +48-22/666-8950, E-mail: wzendzian@wat.edu.pl

diode-pumped laser. The best non-linear crystal for an OPO starting from 1064 nm is KTP 'x-cut' for non-critical phase matching at room temperature. It was shown [14] that the temperature range of efficient parametric generation for such a crystal is (−32 °C, 90 °C); thus a precision temperature control or stabilization is not required.

The characteristic property of an IOPO with a passively Q-switched pump laser is the possibility of generation of a single pulse or a short series of a few pulses with dozens ns intervals [26, 28]. The aim of this paper is the practical demonstration of an efficient high peak power IOPO. For an IOPO with a passively Q-switched Nd:YAG laser pumped by a 300 W-diode array we achieved 1.9-mJ energy at 1572-nm wavelength with a pulse duration of 2.9 ns. To our knowledge, this is the highest peak power of 0.65 MW and efficiency for such a type of single resonant diode-pumped IOPO laser.

2 Experimental setup

Investigations on an IOPO were carried out in the experimental setup shown in Fig. 1. As a pumping unit we have used the passively Q-switched Nd:YAG slab laser (for details see [30]) worked out for a range-finder transmitter operating at 1064-nm wavelength. In such a laser, a single-bounce triangle slab with Brewster-cut faces is pumped by a 300-W quasi-cw diode-laser array SDL 3251-A3 directly attached to the slab base (see Fig. 2). The diode pump unit creates an inversion profile in the active medium, well matched to the TEM_{00} cavity mode, ensuring efficient extraction of energy. Moreover, due to the Brewster-cut slab facets, linear p-polarization in the horizontal plane is enforced in free-running as well as in passively Q-switched regimes.

For a cavity length longer than 10 cm we observed operation in the circular TEM_{00} mode with the diameter of about 0.8 mm. In the laser, optimized for passively Q-switched operation [31], a pulse energy of 5.3 mJ with 12-ns duration was achieved at 1064-nm wavelength. The internal OPO cavity consists of the rear flat mirror M_1 highly reflective at the 1576-nm wavelength and anti-reflective at the pump wavelength, the KTP crystal for non-linear conversion, and the flat output-coupling mirror M_2 highly reflective at the pump wavelength with transmission R_s at the signal wavelength. The KTP crystal (produced by Cassix, Inc.) of 20-mm length 'x-cut' for non-critical phase matching for pump 1064-nm, signal 1572-nm, and idler 3293-nm wavelengths enables the 'walk-off' effect to be eliminated and has a very low temperature sensitivity in the range (−30 °C, 90 °C) [14]. The single resonant IOPO scheme is accomplished in such a way with high losses at the idler wavelength. The pumping laser length was elongated to about 20 cm with an internal OPO cavity of 3-cm length. The rear mirror M of radius of curvature 2 m and high reflectivity at 1064-nm wavelength was used for stabilization of the fundamental mode operation of the pump radiation. To estimate the parameters of such a resonator, measurements of free-running operation without OPO elements and with them were carried out (see Fig. 3). For optimal 15% transmission of the output coupler (OC) the energy of 15.3 mJ for diode pump energy of 52 mJ was achieved at the fundamental wavelength. For 30% transmission of the OC, the lower energy of 12.5 mJ (without the OPO crystal) and 9 mJ for the cavity with OPO elements were achieved, evidencing significant internal losses of the IOPO cavity at the pump wavelength. The effective dissipative loss coefficient at the pump wavelength was estimated as $0.17\ \mathrm{cm}^{-1}$.

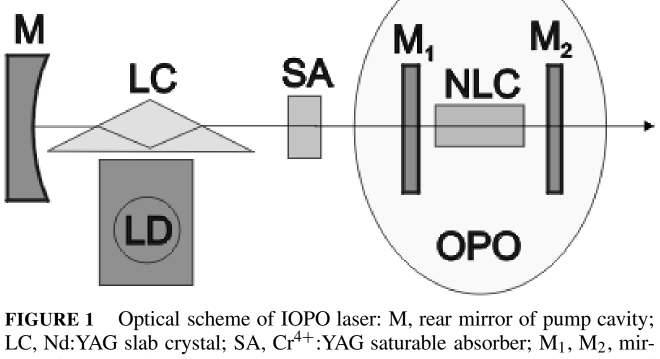

FIGURE 1 Optical scheme of IOPO laser: M, rear mirror of pump cavity; LC, Nd:YAG slab crystal; SA, Cr^{4+}:YAG saturable absorber; M_1, M_2, mirrors of OPO cavity; LD, 2D diode-array stack; NLC, 'x-cut' KTP crystal of $20 \times 5 \times 5\ \mathrm{mm}^3$

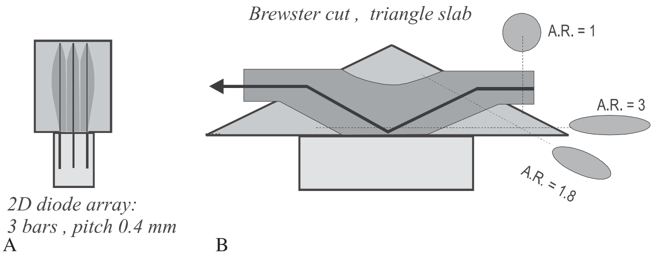

FIGURE 2 Scheme of pumping of Brewster-cut Nd:YAG slab crystal. **A** Vertical section (not to scale) (*left*), **B** horizontal section (*right*). A.R., aspect ratio of the pump area at given section

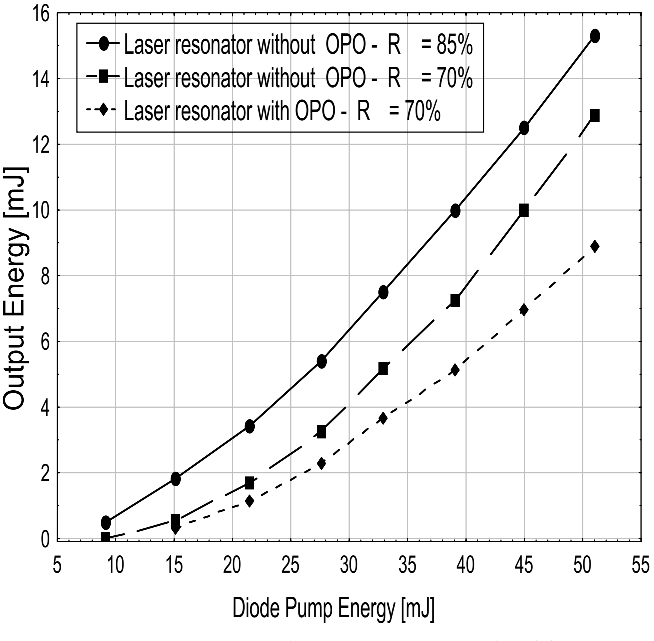

FIGURE 3 Output energy vs. diode pump energy: results of free running operation experiments

3 Results of IOPO characterization

It was shown in numerical analysis given elsewhere [23, 26, 32] that an IOPO acts like a cavity dumper, causing the dump of the signal pulse with pulse width comparable to a resonator round-trip time. The mechanism of signal-pulse build up can be explained in the following way. Firstly, in the pump pulse build up stage, the intensity of the pump non-linearly increases until the threshold of parametric oscillation. Starting at such a point, the non-linear loss for the pump rapidly increases, causing a very fast decrease in pump intensity with simultaneous rapid increase in signal and idler. If the inversion in the active medium is highly depleted, we observe single-pulse generation. The optimization of such a laser consists in the search of the best combination of nonlinearity of the OPO crystal and output-coupler losses with respect to the maximum of signal energy. It was found in the experiments that the efficient passive Q-switching operation of the IOPO starts for Cr^{4+}:YAG passive Q-switches of initial transmission of 52% and 66% (see Fig. 4). The highest signal energy of 1.9 mJ with 2.9-ns duration for the Q-switch of 52% initial transmission, and 0.45-mJ energy with 3-ns duration for the latter, were achieved. In both cases, the optimal

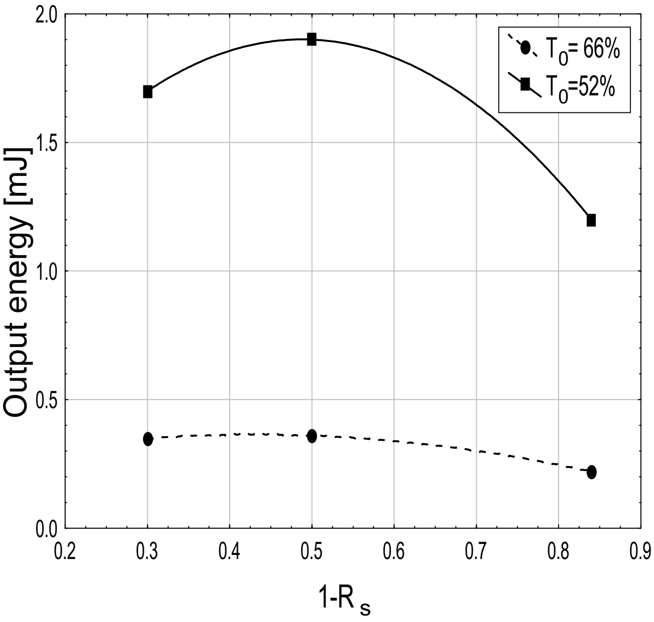

FIGURE 4 Dependence of signal output energy on reflectivity R_s: results of experiments

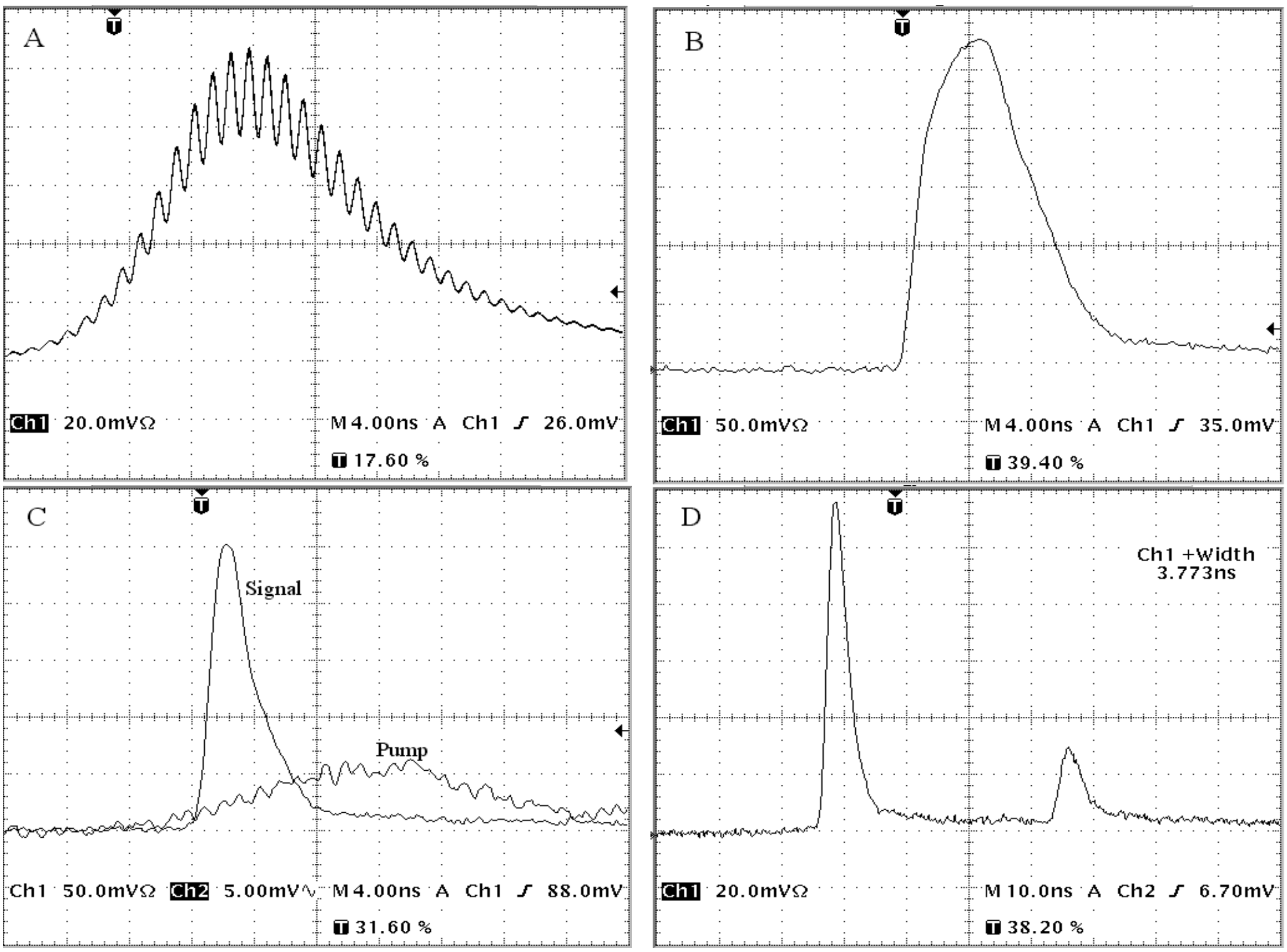

FIGURE 5 Oscillograms of pump and OPO pulses. **A** pump pulse of passively Q-switched Nd:YAG laser with optimum output coupler, **B** signal pulse generated in external OPO pumped by pump laser, **C** signal and pump pulses generated in IOPO with passive Q-switch of 52% initial transmission and output coupler of 50% transmission, **D** series of signal pulses generated in the same IOPO with output coupler of 15% transmission

output-coupler transmission R_s at 1572-nm wavelength was 50%. The highest peak power of 0.65 MW for the best case was achieved mainly due to a very short pulse duration. To compare the results of the IOPO, an experiment on an external single resonant OPO pumped by the same Nd:YAG laser was carried out. In the best case, the same pumping laser has generated the pulses of 4.4-mJ energy and 13-ns duration for the passive Q-switch of 52%, and 1.6-mJ energy and 15-ns duration for the passive Q-switch of 66% initial transmission. The signal energy of 1.5 mJ with 10-ns duration was obtained for the first case and 0.4-mJ energy with 13-ns duration for the second. The temporal characteristics of the pump, external OPO, and IOPO pulses are shown in Fig. 5. The pulses of the IOPO (Fig. 5, trace C) are five-times shorter than the pump pulses (trace A) and about three-times shorter than the pulses generated by the external OPO (trace B). Moreover, a series of two pulses was observed (Fig. 5, trace D) for the IOPO with the lower output-coupling transmission of 15%. A circular, near-TEM_{00} signal beam was observed for a 15-Hz repetition rate. The increase in repetition rate up to 100 Hz is feasible, but with diminishing of the output efficiency and beam quality as a result of an increase in thermally induced aberration in the gain medium.

4 Conclusions

Two regimes of operation of an IOPO laser, namely single-pulse and pulse-series regimes, were demonstrated in the experiment and theoretically explained [32]. The following conclusions concerning optimization of such a laser were drawn and verified in the experiments:

- the main difference between the IOPO and the external OPO pumped by the same pump laser is a much higher peak power due to a significant reduction of signal-pulse duration, whereas the output-pulse energies are comparable,
- for given parameters of the pump pulse, an optimal combination of non-linearity of the OPO converter and the output-coupling losses exists, resulting in generation of a single pulse with the highest peak power,
- the highest peak power and energy are achieved for the shortest length of the IOPO cavity,
- a decrease in the IOPO threshold (i.e. an increase in non-linearity of the OPO converter or a decrease in the output-coupling losses) can result in the transition from the single-pulse regime into the regime of pulse-series generation with lower peak powers but comparable total energy of pulses. The main effect consists in non-complete depletion of gain by the initial, first pulse as a result of too-low threshold of signal-pulse generation. The consecutive pulses can be generated up to complete unloading of the inversion.

We have demonstrated an experimental model of KTP-IOPO with the highest (to our knowledge) peak power of 0.65 MW at 1572-nm wavelength. It generates pulses of 1.9-mJ energy with an optical efficiency of 3.6% with respect to the diode pump. Such an efficient high peak power 'eye-safe' laser can find numerous applications in several areas, i.e. range finding, atmospheric pollution detection, and so on.

ACKNOWLEDGEMENTS This work was supported by the Polish Committee for Scientific Research under Project Nos. 0T00A06519 and 4T11B027724.

REFERENCES

1 M.B. Camargo, R.D. Stultz, M. Birnbaum: Adv. Solid State Lasers OSA TOPS **1**, 454 (1996)
2 M.M. Tilleman, S. Jachel, I. Moshe: Adv. Solid State Lasers OSA TOPS **19**, 162 (1998)
3 S.J. Hamlin, R. Wu, L.A. Bosworth: Adv. Solid State Lasers OSA TOPS **19**, 171 (1998)
4 R.D. Stultz, M.B. Camargo, M. Lawler, D. Rockafellow, M. Birnbaum: Adv. Solid State Lasers OSA TOPS **19**, 155 (1998)
5 P. Thony, B. Ferrand, E. Molva: Adv. Solid State Lasers OSA TOPS **19**, 150 (1998)
6 A. Levoshkin, A. Petrov, J.E. Montage: Opt. Commun. **185**, 399 (2000)
7 J.T. Murray, R.C. Powell, D. Smith, W. Austin, R.A. Stolzenberger: Opt. Lett. **20**, 1017 (1995)
8 N. Takei, S. Suzuki, F. Kannari: in *Tech. Dig. CLEO Pacific Rim'99*, p. 744
9 P. Cerny, H. Jelinkova: Opt. Lett. **27**, 360 (2002)
10 P. Cerny, W. Zendzian, J.K. Jabczyński, H. Jelinkova, J. Sulc, K. Kopczyński: Opt. Commun. **209**, 403 (2002)
11 T. Chuang, J. Kasinski, H.R. Verdun: Adv. Solid State Lasers OSA TOPS **1**, 150 (1996)
12 M. Acharekar, T. Whittaker, G. Xiao, M. Bass: in *Tech. Dig. CLEO '98, Vol. 6*, p. 137
13 Y. Isynova, A. Dergachev, D. Welford, P. Moulton: Adv. Solid State Lasers OSA TOPS **26**, 548 (1999)
14 R.D. Stultz, M.E. Ehritz, E. Segundo: Adv. Solid State Lasers OSA TOPS **1**, 147 (1996)
15 J.A. Armstrong, N. Bloembergen, J. Ducuing, P.S. Pershan: Phys. Rev. **127**, 1918 (1962)
16 K. Daneshvar, D.H. Kang: IEEE J. Quantum Electron. **QE-36**, 85 (2000)
17 M.M. Fejer, G.A. Magel, D.H. Jundt, R.L. Byer: IEEE J. Quantum Electron. **QE-28**, 2631 (1992)
18 W.R. Bosenbeg, A. Drobshoff, J.I. Alexander, L.E. Myers, R.L. Byer: Opt. Lett. **21**, 713 (1996)
19 L.E. Meyrs, G.D. Miller, R.C. Eckardt, M.M. Fejer, R.L. Byer, W.R. Bosenbeg: Opt. Lett. **20**, 52 (1995)
20 J.J. Zayhowski: Opt. Lett. **22**, 169 (1997)
21 T. Ikegami, S. Slyusarew, T. Fukuyama, S. Ohshima: Appl. Phys. B **66**, 719 (1998)
22 W.R. Bosenbeg, A. Drobshoff, J.I. Alexander, L.E. Myers, R.L. Byer: Opt. Lett. **21**, 1336 (1996)
23 J. Falk, J.M. Yarborough, E.O. Ammann: IEEE J. Quantum Electron. **QE-7**, 359 (1971)
24 T. Debuisschert, J. Raffy, J.P. Pocholle, M. Papuchon: JOSA B **13**, 1596 (1996)
25 R. Dabu, A. Stratan, C. Fenic, C. Luculescu, L. Muscalu: Opt. Eng. **40**, 455 (2001)
26 A. Agnesi, S. Dell'Acqua, G. Reali: Appl. Phys. B **70**, 751 (2000)
27 G. Xiao, M. Bass, M. Acharekar: IEEE J. Quantum Electron. **QE-34**, 2241 (1998)
28 Y. Yashkir, H.M. van Driel: Appl. Opt. **38**, 2554 (1999)
29 T. Chuang, R. Burnham: Adv. Solid State Lasers OSA TOPS **26**, 534 (1999)
30 W. Zendzian, J.K. Jabczyński, Z. Mierczyk: Opto-Electron. Rev. **9**, 75 (2001)
31 J.J. Degnan: IEEE J. Quantum Electron. **QE-31**, 1890 (1995)
32 W. Zendzian, J.K. Jabczyński, J. Kwiatkowski: Proc. SPIE **5120**, (2003) in press