Appl. Phys. B 85, 581–584 (2006)
DOI: 10.1007/s00340-006-2454-0

Applied Physics B
Lasers and Optics

V.E. KISEL[1]
N.A. TOLSTIK[1,✉]
A.E. TROSHIN[1]
N.V. KULESHOV[1]
V.N. MATROSOV[2]
T.A. MATROSOVA[2]
M.I. KUPCHENKO[2]
F. BRUNNER[3]
R. PASCHOTTA[3]
F. MORIER-GENOUD[3]
U. KELLER[3]

Spectroscopy and femtosecond laser performance of Yb^{3+}:$Gd_{0.64}Y_{0.36}VO_4$ crystal

[1] Institute for Optical Materials and Technologies, Belorussian National Technical University, 65 Nezavisimosti ave., Build. 17, Minsk, Belarus
[2] Solix Ltd., 77 Partizanski ave., Minsk, Belarus
[3] Institute of Quantum Electronics, Physics Department, Swiss Federal Institute of Technology (ETH), ETH Zürich Hönggerberg, Wolfgang-Pauli-Str. 16, 8093 Zürich, Switzerland

Received: 3 March 2006/Revised version: 21 July 2006
Published online: 6 October 2006 •

ABSTRACT We report for the first time on the efficient continuous-wave and mode-locked laser operation of a diode-pumped Yb:$Gd_{0.64}Y_{0.36}VO_4$ laser. cw output power of 855 mW with a slope efficiency of 45% with respect to the absorbed pump power was demonstrated for the 2.1%-doped crystal. In mode-locked regime with SESAM as passive shutter pulses as short as 100 fs were obtained.

PACS 42.55.Xi; 42.65.Re; 42.70.Hj

1 Introduction

During the last few years, ytterbium-doped laser crystals have been intensively investigated, first of all from the point of view of the development of reliable and efficient femtosecond lasers. The shortest pulses were obtained with Yb^{3+}:$CaGdAlO_4$ crystal with extracavity pulse compression (47 fs [1]). Sub 100-fs pulses were recently also obtained with Yb^{3+}:$Sr_3Y(BO_3)_3$ [2], Yb^{3+}:$Sr_3Y_4(SiO_4)_3O$ [3], Yb^{3+}:$KY(WO_4)_2$ [4] and Yb^{3+}:YVO_4 [5] crystals, phosphate and silicate [6] glasses.

Yb:YVO_4 crystal is a promising Yb-doped laser medium due to strong absorption band near 985 nm, comparatively high thermal conductivity, and broad gain bandwidth. Laser action of Yb^{3+} in YVO_4 was demonstrated in continuous-wave (cw) [7, 8], Q-switched [9] and mode-locked [5, 10] regimes. The mode-locked pulse duration of about 120 fs was demonstrated with semiconductor saturable absorber mirror [10] and 61 fs in the case of Kerr-lens mode-locking technique [5].

For further shortening of the mode-locked pulses, it is necessary to broaden the gain bandwidth of the material. One of the possible ways is to use the disordered crystal host. Disordered crystals with inhomogeneous line broadening occupy intermediate position between ordered laser hosts and glasses with respect to their thermomechanical and spectroscopic properties. Laser operation of Yb^{3+} in disordered molybdates and tungstates was reported in several works [11, 12]. In mixed yttrium-gadolinium vanadate a locally variable crystal field around the dopant ion is observed and the linewidths of the electronic transitions for the rare earth elements are found to be broader than in ordered crystals.

In this work we report for the first time to our knowledge on the spectroscopy, continuous wave and mode-locked laser operation of Yb^{3+}:$Gd_{0.64}Y_{0.36}VO_4$ disordered crystal at room temperature. A comparison of its laser properties with those of ordered Yb^{3+}:YVO_4 crystal has been performed.

2 Crystal growth

The crystals were grown by Solix Ltd. by using the Czochralski technique in iridium crucible in argon atmosphere containing oxygen. A pulling rate was of about 2–3 mm/h with rotation speed of 10–15 revolutions per minute. The boules of Yb:$GdYVO_4$ single crystals of high optical quality 30 mm in diameter and 35 mm in length with 2.1 at. % of Yb concentration were produced.

3 Spectroscopy

The room-temperature polarized absorption spectra of Yb^{3+}:$Gd_{0.64}Y_{0.36}VO_4$ crystal measured with spectral resolution of 0.4 nm are shown in Fig. 1. A strong absorption band with cross-section of 7.5×10^{-20} cm^2 centered at 985 nm (that corresponds to the zero phonon line) was observed in π-polarization ($E||c$). In σ-polarization two local maxima of about 2.3×10^{-20} cm^2 and 1.8×10^{-20} cm^2 are located at 964 and 985.6 nm, respectively.

The comparison of zero phonon lines of ytterbium-doped YVO_4 and $GdYVO_4$ crystals at 10 K and at room temperature is shown in Fig. 2. At low temperature the linewidth of $GdYVO_4$ is about 1 nm that is broader than in YVO_4 (0.3 nm) due to inhomogeneous line broadening caused by crystal structure disordering. Room temperature zero phonon linewidth (FWHM) of mixed vanadate was measured to be 9.5 nm, and this value is about 1.5 nm higher than in yttrium vanadate (∼8 nm). It may be connected both with inhomo-

✉ Fax: +375-17-2926286, E-mail: ntolstik@bntu.by

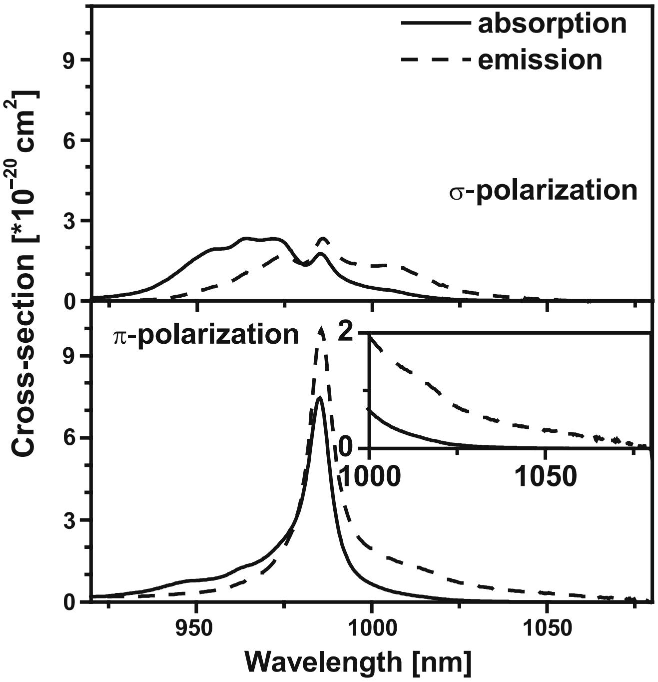

FIGURE 1 Room-temperature polarized absorption (*solid lines*) and emission (*dashed lines*) spectra of Yb^{3+}:$Gd_{0.64}Y_{0.36}VO_4$ crystal

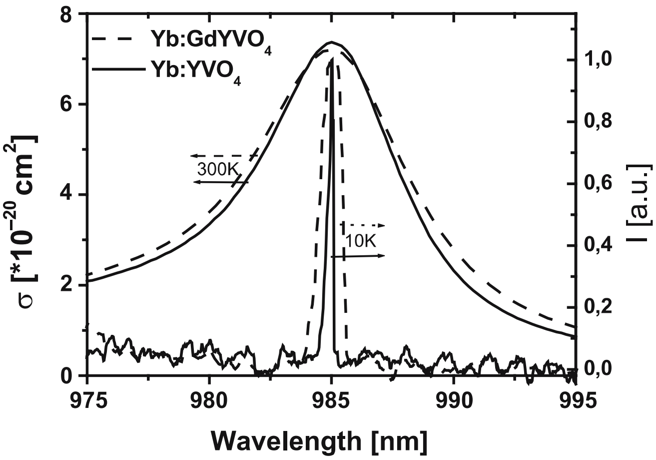

FIGURE 2 Comparison of zero phonon absorption lines in $Yb:YVO_4$ (*solid line*) and $Yb:GdYVO_4$ (*dashed line*) crystals at room temperature (scale on the left) and at 10 K (scale on the right)

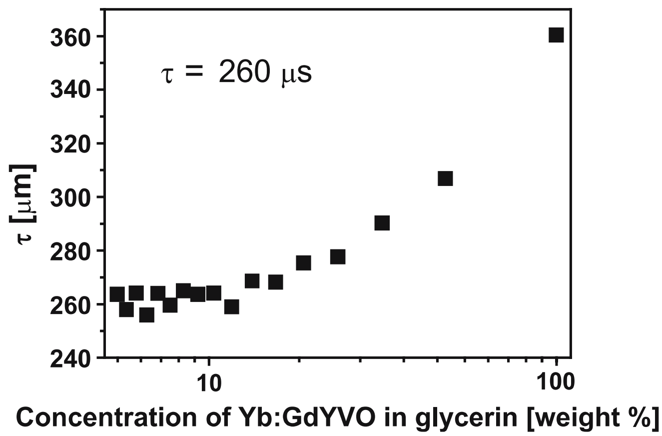

FIGURE 3 Lifetime of the Yb(2.1 at. %):$Gd_{0.64}Y_{0.36}VO_4$ crystalline powder immersed in glycerin

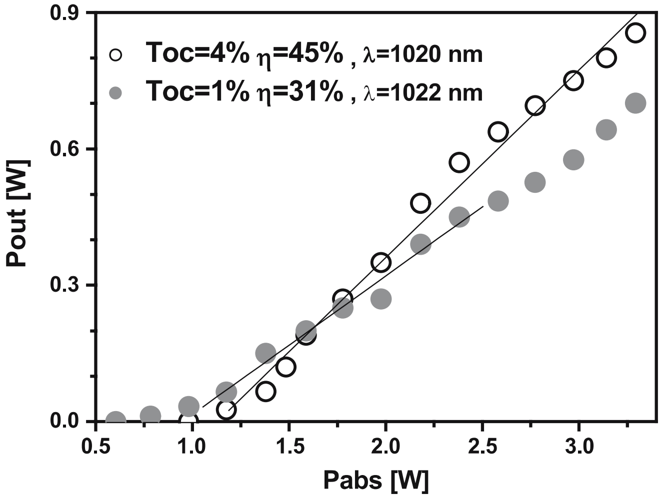

FIGURE 4 Output power versus absorbed pump power of a cw $Yb:GdYVO_4$ laser

geneous line broadening and with broader Yb linewidth in $GdVO_4$ (10 nm [13]).

For lifetime measurements we used a fine powder of Yb(2.1 at. %):$Gd_{0.64}Y_{0.36}VO_4$ crystal immersed in glycerine in order to suppress reabsorption and total internal reflection. The sample was excited by Nd:YAG laser-pumped optical parametric oscillator tuned to 985 nm. The emitted luminescence was measured using 0.3-m monochromator, fast Ge photodiode and 500-MHz digital oscilloscope. The experiment showed that the measured lifetime decreased with decreasing of weight concentration of crystal powder in suspension. Starting from certain powder concentration the measured value remained practically constant despite further dilution (Fig. 3). This invariability of measured lifetime at low concentrations indicates that reabsorption effects became negligible. Thus the lifetime of Yb^{3+} ion in $GdYVO_4$ was measured to be (260 ± 5) μs, that is not far from the lifetime of Yb^{3+} in YVO_4 247 ± 5 μs [7]).

The emission cross section spectra were calculated using modified reciprocity method [14]:

$$\sigma_{\mathrm{em}}^{\alpha}(\lambda) = \frac{3 \times \exp(-hc/(kT\lambda))}{8\pi n^2 \tau_{\mathrm{rad}} c \left[\sum_{\beta} \int \lambda^{-4} \sigma_{\mathrm{abs}}^{\beta}(\lambda) \exp(-hc/(kT\lambda))\, \mathrm{d}\lambda \right]} \sigma_{\mathrm{abs}}^{\alpha}(\lambda) \quad (1)$$

where τ_{rad} is the radiative lifetime of an active center, c is the velocity of light, α is a light polarization, h and k are the Planck's and Boltzman's constants, respectively, T is a host crystal temperature, n is the refractive index of a crystal, β denotes the polarization state and σ_{abs} is the ground state absorption cross section.

The emission cross-section spectra are shown in Fig. 1. The stimulated emission cross sections were calculated to be $0.9 \times 10^{-20}\,\mathrm{cm}^2$ and $0.6 \times 10^{-20}\,\mathrm{cm}^2$ at 1020 nm for π and σ polarizations, respectively.

4 Laser experiments

The cw laser experiments were carried out with a nearly hemispherical laser cavity. The pumping was realized through the plane input mirror highly reflecting at 1020–1100 nm. Different output couplers with radius of curvature 50 mm and transmittance 1% and 4% at the laser wavelength were tested. As a pump source a cw fiber-coupled laser diode (∅ = 100 µm, NA = 0.22) operated around 980 nm was used with a spectral bandwidth of 6 nm and maximal output power of 8 W. The transmission of the input mirror at pump wavelength was only 63% thus reducing maximal incident pump power at the crystal down to 5 W. The 2mm-thick Yb(2.1 at. %):$Gd_{0.64}Y_{0.36}VO_4$ crystal absorbed about 65% of the incident pump power. The crystal was antireflection coated at pump and laser wavelengths and placed near the input mirror. The pump radiation was focused to a 110-µm spot inside the crystal. The cavity-mode diameter for the TEM_{00} transverse mode at the active element was close to the pump beam waist.

The input-output diagrams for the cw laser operation of Yb:$GdYVO_4$ are shown in Fig. 4. Maximal output power of 855 mW at 1020 nm was obtained with 4% output coupler transmittance. The slope efficiency of 45% was measured with respect to the absorbed pump power. In the case of 1% output coupler transmittance the maximal output power decreased down to 700 mW, the slope efficiency decreased to 31% and the laser wavelength shifted to 1027 nm. Laser thresholds for 1% and 4% output couplers were determined to be 0.7 W and 1 W of absorbed pump power, respectively. The laser output was π-polarized at both wavelengths.

The femtosecond laser experiments were performed using simple delta cavity setup (Fig. 5). The 2-mm thick Yb (2.1 at. %):$Gd_{0.64}Y_{0.36}VO_4$ laser crystal was placed inside the cavity at Brewster's incidence and mounted on a copper heat sink kept at 10 °C. As the laser output was π-polarized in cw experiments, the active element was cut to operate in π-polarization. As a pump source we used the same diode as in cw experiments. The pumping was performed through the spherical mirror M1. The pump beam was collected to a 110 × 220 µm spot inside the active element by the 4-lens objective with numerical aperture of 0.22, focal length of 125 mm and magnification of 1. There were two factors reducing maximal absorbed pump power at the crystal: low transmittance of the mirror M1 for the pump radiation because of a low spectral shift between pump and laser wavelengths and unpolarized emission of a pump source. Thus maximal absorbed pump power at the crystal was reduced down to 2.4 W.

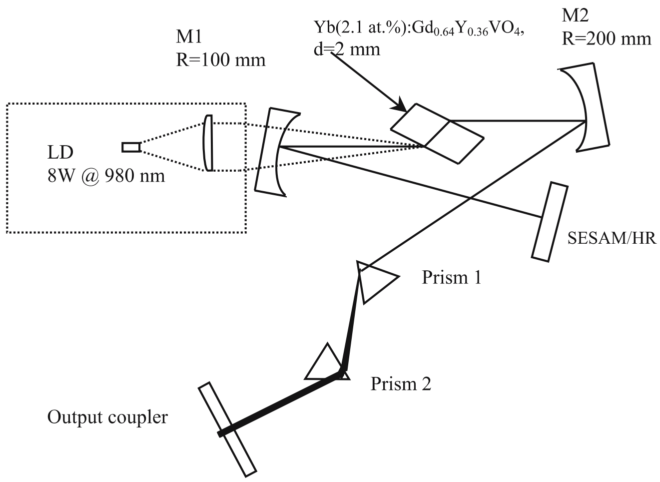

FIGURE 5 Setup of the passively mode-locked diode-pumped Yb:$GdYVO_4$ laser

For passive mode-locking we used a semiconductor saturable absorber mirror (SESAM) with a 15-nm-thick InGaAs quantum-well absorber and a Bragg mirror centered at 1040 nm. The modulation depth was about 1%. The negative group delay dispersion of 3000 fs^2 as needed for soliton mode-locking [15] was achieved by using a pair of SF-10 prisms with 45 cm spacing.

Average mode-locked output power of 120 mW was obtained for the 1.5% output coupler transmittance. The

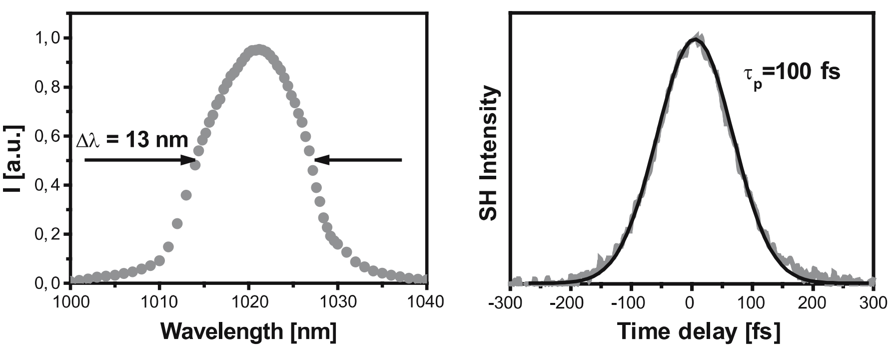

FIGURE 6 Optical spectrum (left) and intensity autocorrelation (right) with $sech^2$ fit of the Yb:$GdYVO_4$ laser

Crystal	$\Delta\lambda_{pump}$ [nm]	$\Delta\lambda_{SE}$ for $\beta = 0.2$ [nm]	τ_{em} [µs]	cw laser: Average power [mW]	cw laser: Slope efficiency [%]	Mode-locked laser: Average power [mW]	Mode-locked laser: Pulse duration [fs]
Yb:$GdYVO_4$	9.5	∼ 33.5	260	855	45	120	100
Yb:YVO_4*	8.0	∼ 32	247	610	49	300	120

* Data taken from [7, 10]

TABLE 1 Crystal properties and laser characteristics of Yb-doped YVO_4 and $GdYVO_4$

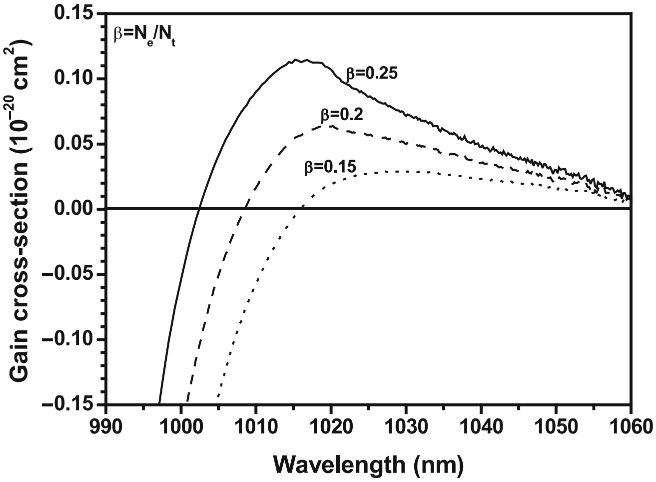

FIGURE 7 π-polarized gain cross-section spectra of Yb^{3+} in $GdYVO_4$ at room temperature for different values of excitation parameter β

pulse duration was about 100 fs, that is shorter than for the $Yb:YVO_4$ mode-locked laser in the similar experimental conditions (120 fs [10]). The emission bandwidth in mode-locked regime was ∼13 nm centered at 1021 nm resulting in the time-bandwidth product of 0.35, not far from the transform limit for soliton pulses. The intensity autocorrelation and optical spectrum of the $Yb:GdYVO_4$ laser are presented in Fig. 6.

The effective gain cross-section spectra were calculated using the following formula [16]:

$$g(\lambda) = \beta\sigma_{se}(\lambda) - (1-\beta)\sigma_{abs}(\lambda)\,, \qquad (2)$$

where $\beta = N_e/N_t$ is the ratio of the number of excited ions to the total number of ions, σ_{se} and σ_{abs} are the stimulated emission and absorption cross section, respectively. The spectra for three different values of excitation parameter β (including $\beta = 0.2$ corresponding to the cavity losses in mode-locked $Yb:GdYVO_4$ laser) are plotted at Fig. 7. The FWHM gain bandwidth of $Yb:GdYVO_4$ crystal for $\beta = 0.2$ is found to be 33.5 nm, that is 1.5 nm broader in comparison with that of $Yb:YVO_4$ crystal (32 nm [10]) and allow one to obtain shorter pulses.

The comparison of several laser-related properties of Yb-doped YVO_4 and $GdYVO_4$ crystals and output characteristics of lasers based on these crystals are shown in Table 1.

5 Conclusion

In conclusion, continuous-wave and mode-locked laser operation of Yb^{3+}:$Gd_{0.64}Y_{0.36}VO_4$ disordered crystal was demonstrated for the first time to our knowledge. Average cw output power of 855 mW with 45% slope efficiency was achieved for the 2.1%-doped crystal with hemispherical cavity. The mode-locked pulse duration of about 100 fs was obtained that is 20 fs shorter than for Yb^{3+}:YVO_4 crystal at the same experimental conditions. Results indicate that disordered vanadate crystals look promising for the shortening of femtosecond pulse duration.

REFERENCES

1 Y. Zaouter, J. Didierjean, F. Balembois, G.L. Leclin, F. Druon, P. Georges, J. Petit, P. Goldner, B. Viana, Opt. Lett. **31**, 119 (2006)
2 F. Druon, S. Chenais, P. Raybaut, F. Balembois, P. Georges, R. Gaume, G. Aka, B. Viana, S. Mohr, D. Kopf, Opt. Lett. **27**, 197 (2002)
3 F. Druon, S. Chenais, P. Raybaut, F. Balembois, P. Georges, R. Gaume, P.H. Hausmesser, B. Viana, D. Vivien, S.S. Dhellemmes, V. Ortiz, C. Larat, Opt. Lett. **27**, 1914 (2002)
4 F.H. Liu, J. Nees, G. Mourou, Opt. Lett. **26**, 1723 (2001)
5 A.A. Lagatsky, A.R. Sarmani, C.T.A. Brown, W. Sibett, V.E. Kisel, A.G. Selivanov, I.A. Denisov, A.E. Troshin, K.V. Yumashev, N.V. Kuleshov, V.N. Matrosov, T.A. Matrosova, M.I. Kupchenko, Opt. Lett. **30**, 3234 (2005)
6 C. Honninger, F. Morier-Genoud, M. Moser, U. Keller, L.R. Brovelli, C. Harder, Opt. Lett. **23**, 126 (1998)
7 V.E. Kisel, A.E. Troshin, N.A. Tolstik, V.G. Shcherbitsky, N.V. Kuleshov, V.N. Matrosov, T.A. Matrosova, M.I. Kupchenko, Opt. Lett. **29**, 2491 (2004)
8 C. Krankel, D. Fagundes-Peters, S.T. Fredrich, J. Johannsen, M. Mond, G. Huber, M. Bernhagen, R. Uecker, Appl. Phys. B **79**, 543 (2004)
9 V.E. Kisel, A.E. Troshin, N.A. Tolstik, V.G. Shcherbitsky, N.V. Kuleshov, V.N. Matrosov, T.A. Matrosova, M.I. Kupchenko, Appl. Phys. B **80**, 471 (2005)
10 V. Kisel, A. Troshin, V. Shcherbitsky, N. Kuleshov, V. Matrosov, T. Matrosova, M. Kupchenko, F. Brunner, R. Paschotta, F. Morier-Genoud, U. Keller, Opt. Lett. **30**, 1150 (2005)
11 M. Rico, J. Liu, U. Griebner, V. Petrov, M.D. Serrano, F. Esteban-Betegon, C. Cascales, C. Zaldo, Opt. Express **12**, 5362 (2004)
12 J. Liu, J.M. Cano-Torres, C. Cascales, F. Esteban-Betegón, M.D. Serrano, V. Volkov, C. Zaldo, M. Rico, U. Griebner, V. Petrov, Phys. Stat. Solidi A **202**, R29 (2005)
13 Y. Sato, J. Saikawa, T. Taira, O. Nakamura, Y. Furukawa: Conference on Advanced Solid-State Photonics (2005), Vienna, Austria, Technical Digest, paper MF8.
14 A.S. Yasukevich, V.E. Kisel, V.G. Shcherbitsky, A.V. Mandrik, N.V. Kuleshov, J. Appl. Spectrosc. **71**, 202 (2004)
15 F.X. Kartner, U. Keller, Opt. Lett. **20**, 16 (1995)
16 C. Li, R. Moncorge, J.C. Souriau, C. Borel, C. Wyon, Opt. Commun. **107**, 61 (1994)