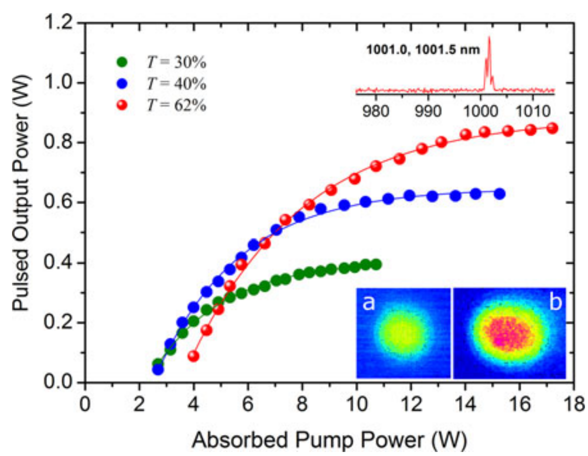
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Generation of Pulsed Laser Radiation at 1002 nm with a Quantum Defect of 2.6%

Volume 9, Number 3, June 2017

Xiaodan Dou
Lisha Wang
Yanjun Ma
Wenjuan Han
Honghao Xu
Degao Zhong
Bing Teng
Junhai Liu



DOI: 10.1109/JPHOT.2017.2703782

Generation of Pulsed Laser Radiation at 1002 nm with a Quantum Defect of 2.6%

Xiaodan Dou, Lisha Wang, Yanjun Ma, Wenjuan Han, Honghao Xu, Degao Zhong, Bing Teng, and Junhai Liu

College of Physics, Qingdao University, Qingdao 266071, China

DOI:10.1109/JPHOT.2017.2703782

Manuscript received April 4, 2017; revised May 5, 2017; accepted May 9, 2017. Date of publication May 12, 2017; date of current version May 29, 2017. This work was supported by the National Natural Science Foundation of China under Grants 11574170 and 11374170. Corresponding author: Junhai Liu (e-mail: junhai_liu@hotmail.com).

Abstract: Low-quantum-defect pulsed oscillation at 1002 nm was achieved with a $Yb:LuPO_4$ miniature crystal rod laser longitudinally pumped by a 976-nm diode laser, with a GaAs semiconductor saturable absorber to induce passive Q-switching. With 17.2 W of pump power absorbed in the crystal rod, an average output power of 0.85 W was generated at a repetition rate of 3.7 kHz, the resulting pulse energy, duration, and peak power were 230 μJ, 5.5 ns, and 41.8 kW, respectively.

Index Terms: Yb laser, Q-switched, $Yb:LuPO_4$ crystal, GaAs saturable absorber.

1. Introduction

Laser radiation in the near-infrared 1.0−1.1 μm spectral region is usually generated through the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of the Nd^{3+} ion or the $^2F_{5/2} \rightarrow {}^2F_{7/2}$ transition of the Yb^{3+} ion. In some sense, Yb-ion lasers are superior to their Nd-ion counterparts, owing to their absence of excited-state absorption; little or no concentration quenching; and in particular, the small quantum defect that leads to low thermal load, facilitating high-power or high-repetition rate laser operation [1]. For the typical Yb:YAG laser operating at 1030 nm that is usually pumped by 941-nm diode, the quantum defect fraction, 0.09, is less than half that for the traditional Nd:YAG laser (0.24) [1].

So far a wide variety of Yb-ion laser crystals have been developed, of which many can be pumped at wavelengths around 976 nm. This wavelength coincides with the emission of currently easily available InGaAs diode lasers. When pumped at 976 nm, an Yb-ion laser can be of an even further reduced quantum defect. As long as the quantum defect is concerned, the crystal of Yb-doped lutetium orthophosphate, $Yb:LuPO_4$, seems to be very attractive. This crystal can be efficiently pumped by a 976-nm diode, since its strongest absorption band is peaked at 975 nm with a bandwidth of 14 nm [2]. More importantly, there exists a strong emission peak at about 1000 nm, where the emission cross-section is roughly three times larger than the absorption cross-section [2], making it feasible to achieve laser action with a very small quantum defect.

In the early years of Yb-ion lasers, the $Yb:LuPO_4$ crystal had attracted some attention [3]. However, due to the difficulty in crystal growth of orthophosphates [4], it proves to be a formidable challenge to grow large-size $Yb:LuPO_4$ crystal of high optical quality. In fact, it was not until 2014 that continuous-wave (CW) laser action was realized with a 0.3 mm thick crystal plate (rectangular aperture of 5.0 mm × 2.0 mm) [2]. Since then, miniature columnar crystals of $Yb:LuPO_4$

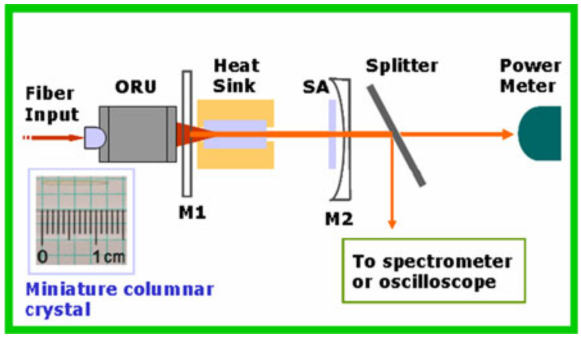


Fig. 1. Schematic diagram of the experimental laser set up. ORU: optical re-imaging unit; SA: saturable absorber.

have been grown successfully employing the high-temperature solution method [5]. With such a miniature crystal rod, we have demonstrated that high-power CW, actively Q-switched, or passively Q-switched (with a Cr^{4+}:YAG saturable absorber) laser operation could be achieved, with output power reaching 6−7 W level [6], [7].

In this paper we report on the generation of pulsed laser radiation at 1002 nm with a quantum defect as low as 2.6%, from an Yb:$LuPO_4$ miniature crystal rod laser, which was passively Q-switched by a GaAs semiconductor saturable absorber. The oscillation of the pulsed laser occurred exactly at the emission peak of Yb:$LuPO_4$ crystal for σ polarization [2]. The laser wavelength achieved here seems to be the closest to 1 μm, among the Yb-ion lasers pumped by 976-nm diodes.

2. Experimental Details

The miniature columnar crystal of Yb:$LuPO_4$, utilized in the experiment, was grown along its crystallographic *c* axis from spontaneous nucleation in high temperature solution [5]. A picture of a typical as-grown crystal is presented in the left lower part of Fig. 1. The crystal sample employed was 2 mm long, with transverse dimension of about 0.7 mm; it was cut directly from a columnar crystal, with two end faces polished but not coated. The Yb-ion concentration of the crystal was 5 at. %, corresponding to 6.15×10^{20} cm^{-3}. As the saturable absorber for passive Q-switching, a 0.5 mm thick un-doped GaAs crystal plate, which was cut along the [100] crystallographic direction, was utilized. Antireflection (AR) coatings were deposited on both surfaces of the GaAs plate. The pulsed Yb:$LuPO_4$/GaAs laser was fabricated with a plano-concave resonator, as illustrated schematically in Fig. 1. The plane mirror M1 was coated for high reflectance (>99.9%) at 1020−1200 nm, and for high transmittance (>95%) at 800−980 nm; M2 was a concave mirror having a radius-of-curvature of 100 mm, and served as the output coupler. The transmittance (output coupling) of the coupler employed in the pulsed laser was $T = 30\%$, 40%, or 62%. For efficient laser action, the miniature Yb:$LuPO_4$ rod was fitted into a copper heat sink, which was cooled by cycling water maintained at a temperature of 5 °C. This was the lowest water temperature allowed in the current experiment. In general, lower cooling temperature is desirable for achieving more efficient laser action, in particular for a quasi-three-level system. It was observed in our experiment that raising the water temperature from 5 °C to 10 °C had only modest effect on the laser performance. Inside the resonator the Yb:$LuPO_4$ crystal rod was placed close to the plane mirror; while the GaAs saturable absorber (SA) was positioned near the output coupler. The physical cavity length of the laser resonator was 99 mm. As the pump source for the laser, a fiber-coupled diode laser emitting at 976 nm (bandwidth of less than 0.5 nm), with fiber core diameter of 200 μm and NA of 0.22, was employed. The pump beam from the fiber end was focused by a re-imaging unit (ORU), and was delivered into the crystal rod with a pump spot radius of about 70 μm. Through a calibrated beam splitter, the pulsed

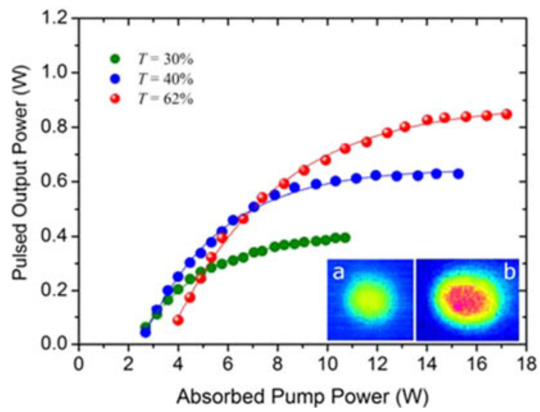


Fig. 2. Pulsed output power versus absorbed pump power measured for the Yb:$LuPO_4$/GaAs laser under different operational conditions. Inset: beam patterns recorded at a low pump level just above threshold (a) and at $P_{abs} = 15.6$ W (b) in the case of $T = 62\%$.

output power and the emission spectrum or the temporal laser parameters could be measured simultaneously by power meter, spectrometer, or digital oscilloscope.

3. Results

The initial or unsaturated absorption of a saturable absorber plays a key role in determining the performance of a passively Q-switched laser. The saturable absorption of un-doped GaAs crystal in the 1-μm spectral region is not caused by valence- to conduction-band electronic transition, as the band gap (1.42 eV) proves to be much greater than the photon energy of the radiation in this region. In fact, it is the EL2 deep donor levels locating at 0.82 eV below the conduction band that result in this saturable absorption [8], [9]. The unsaturated absorption coefficient can be expressed as $\alpha_0 = \sigma_e(N - N^+) + \sigma_h N^+$. In this expression, N denotes the total concentration of EL2 donors; N^+ represents the concentration of $EL2^+$, the ionized EL2 donors for the necessary electric compensation with the negatively charged acceptors [8]; while σ_e and σ_h represent, respectively, the absorption cross-sections for the electronic transition from EL2 to conduction band, and from valence band to $EL2^+$ trap. Since σ_e is greater than σ_h by a factor of 6.5 around 1000 nm ($\sigma_e = 1.3 \times 10^{-16}\,\mathrm{cm}^2$, $\sigma_h = 0.2 \times 10^{-16}\,\mathrm{cm}^2$ at a temperature of 300 K [10]), absorption saturation will occur at sufficiently high radiation intensity, leading to a saturated absorption coefficient $\alpha_{sat} = \sigma_h N$.

To estimate the initial or small-signal transmission of the GaAs crystal plate, we determined the unsaturated absorption coefficient at 1002 nm as $\alpha_0 = 1.62\,\mathrm{cm}^{-1}$, by measuring the transmission curve of an uncoated crystal plate. The initial transmission of the 0.5 mm thick GaAs crystal plate was then calculated to be $T_0 = 92.2\%$; while the actual value for the AR-coated crystal plate was measured as 90.0%, implying the presence of residual Fresnel reflection loss of 2.2%.

With the resonator configuration described in the preceding section, pulsed operation of the Yb:$LuPO_4$/GaAs laser was realized under different output coupling conditions of $T =$ 30%, 40%, and 62%. Fig. 2 shows the pulsed output power as a function of absorbed pump power (P_{abs}), measured in different cases. The absorbed pump power was calculated from the incident pump power by $P_{abs} = \eta_a P_{in}$, with η_a denoting small-signal or unsaturated absorption. For the 2 mm long Yb:$LuPO_4$ crystal rod, the amount of η_a was estimated as 94%, by measuring the residual pump power behind the crystal under non-lasing conditions. This might overestimate the absorbed pump power and accordingly underestimate the laser efficiency. One sees that the variation of output power with P_{abs} was similar for different output couplings. In an initial stage, the output power could increase linearly with P_{abs}; its growth then became slower; and eventually would reach a level that remained nearly unchanged with further increasing pump power. The saturation of out-

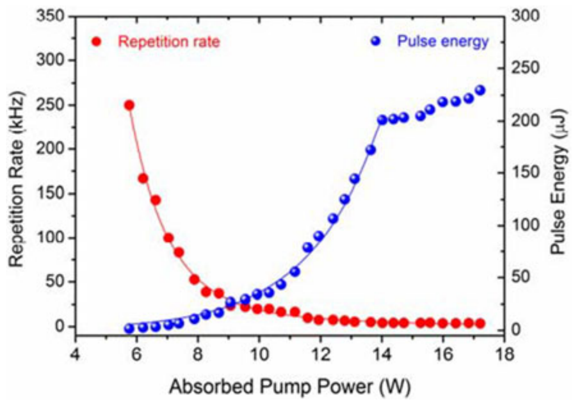


Fig. 3. Variations of repetition rate and pulse energy with absorbed pump power, measured for the case of $T = 62\%$.

put power was due to the increasingly strengthened losses that resulted mainly from the two-photon absorption and free-carrier absorption occurring in the GaAs crystal when the intra-cavity circulating laser intensity became sufficiently strong. The slope efficiencies for the linear stage of the laser action were determined as 9.5%, 13%, and 16%, for $T = 30\%$, 40%, and 62%, respectively. It was also observed that the pulsed operation in the initial linear stage was not stable, owing to the very limited, incomplete bleaching of the GaAs plate. In fact, only the saturable absorption of the GaAs plate was completely saturated, could stable pulsed laser action be achieved, this occurred at $P_{abs} = 12.8$ W for $T = 62\%$. The corresponding critical pump level was found to be $P_{abs} = 4.9$ W for $T = 30\%$; and $P_{abs} = 7.9$ W for $T = 40\%$. Under conditions of a smaller output coupling, the resulting internal laser intensity would be enhanced, making it easier for the GaAs plate to be bleached, and hence a lower pump level required for achieving stable Q-switched laser operation. Clearly, the laser operation obtained with $T = 62\%$ proved to be the most effective, producing a maximum output power of 0.85 W at $P_{abs} = 17.2$ W, compared to 0.40 W and 0.63 W measured in the cases of $T = 30\%$ and $T = 40\%$.

It may be worth pointing out that the plane reflector (M1) was coated for high reflectance (>99.9%) over 1020−1200 nm. A lower reflectance of 98.5% was measured at 1002 nm, which was the actual emission wavelength of the pulsed laser. Due to the small leakage from the plane reflector, the output power obtained from the concave coupler (M2) would be less than the total output generated by the laser, which was, depending on the output coupling in the range of 30%−62%, roughly 1.02−1.05 times higher than reported above.

The profile of the output beam was found to vary with pump level, since more higher-order transverse modes would be able to get lasing with the increase of pump power. The inset in Fig. 2 shows two beam patterns, measured at a low pump level just above the laser threshold (a), and at a high pump power of $P_{abs} = 15.6$ W (b) in the case of $T = 62\%$.

It was found experimentally that the position of the GaAs crystal plate in the resonator played a crucial role in determining the pulsed laser performance. To generate high-energy, short-duration laser pulses, the position of the GaAs plate was optimized to be as close as possible to the concave output coupler. Placing the GaAs saturable absorber near the laser crystal would lead to worse laser performance.

Fig. 3 shows the pulse repetition rate versus absorbed pump power, along with the pulse energy as a function of P_{abs}, plotted for the case of $T = 62\%$. The pulse energy was determined from the average output power and the corresponding repetition rate. Upon raising the pump power, the pulse repetition rate decreased while the pulse energy increased; this was connected with the progressively increased degree to which the GaAs saturable absorber was bleached. Once the bleaching was completed, the repetition rate would remain unchanged or was reduced very slightly, due to the increase of linear losses arising perhaps from thermal effects in the GaAs as well as in

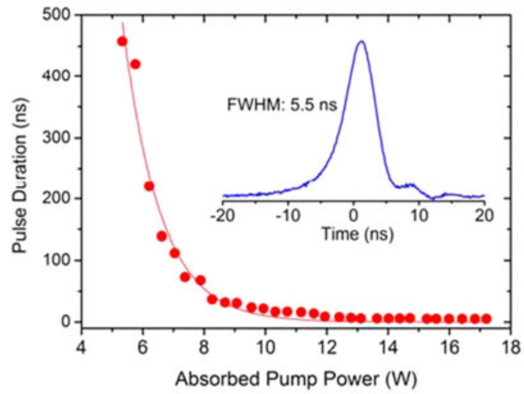


Fig. 4. Dependence of pulse duration on absorbed pump power, measured for the case of $T = 62\%$. Inset: temporal profile of the shortest laser pulse.

the $Yb:LuPO_4$ crystal rod. Accordingly, the pulse energy increased only moderately in this region, from 201 to 230 μJ. The pulse repetition rate, reached at the highest pump power of $P_{abs} = 17.2$ W, was 3.7 kHz; while the pulse energy generated at this pump level was 230 μJ.

As shown in Fig. 3, the pulse repetition rate decreased with increasing pump power, which seems to be contrary to the behavior of usual passive Q-switching laser action. Due to the large mode size at the position of the GaAs crystal plate, the laser intensity achievable over the low-pump region was fairly limited, and hence the GaAs absorber could only be partially bleached. In this situation, the effective saturable absorption, or the modulation depth, of the GaAs absorber was actually pump power dependent, increasing from a very small amount to a maximum value $(1 - T_0)$. This interprets the unusual variation behavior of pulse repetition rate with pump power.

From Fig. 3 one sees that the reduction of repetition rate can be fitted approximately to an exponential decay curve; whereas the increase of pulse energy follows roughly an exponentially growing curve. These fittings are made to show the variation trends exhibited by the relevant laser parameters. Having little or no direct physical significance, the parameters describing these fitted curves will not be discussed. It is also noticeable that in excess of $P_{abs} = 14.0$ W, the pulse energy, instead of growing exponentially, became varying slightly. This is a clear indication that within this high pump power region, the GaAs saturable absorber had been completely bleached, and the laser thus operated in the ordinary passive Q-switching mode, with pulse energy remaining constant or changing slightly.

Fig. 4 shows the dependence of pulse duration on absorbed pump power for the case of $T = 62\%$. The rapid dropping of pulse duration with increasing pump power, occurring in the initial stage of the pulsed laser action, was again attributed to the increasingly strengthened absorption saturation of the GaAs crystal plate. Once the GaAs absorber became bleached completely, the laser would enter a usual passively Q-switched operational region, in which the pulse duration would no longer change, just as predicted by the standard theory of passive Q-switching. The inset of Fig. 4 presents a temporal profile of the shortest laser pulse, whose duration was 5.5 ns (FWHM). It is noted that the pulse shape was not symmetric, with the trailing edge dropped more sharply. This resulted from free-carrier absorption occurring in the GaAs crystal. Due to the high peak circulating intensity that could be established inside the resonator, two-photon absorption, a third-order nonlinear optical effect proportional to the square of the intensity, would be very effective in the GaAs crystal at the peak of the laser pulse, generating a significant number of free electrons in the conduction band and free holes in the valence band. These free carriers, having lifetimes of several tens of nanoseconds [9], would induce considerable absorption losses, accelerating the decay process of the intra-cavity laser intensity, and thus leading to a sharp trailing edge of the pulse profile.

Fig. 5 illustrates a laser pulse train for the case of $T = 62\%$, which was measured at $P_{abs} = 15.3$ W where the pulse duration had reached its shortest, the repetition rate was 4.3 kHz.

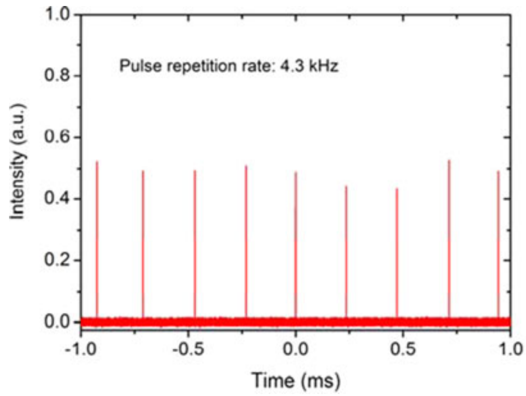


Fig. 5. A laser pulse train showing a repetition rate of 4.3 kHz, measured at $P_{abs} = 15.3$ W in the case of $T = 62\%$.

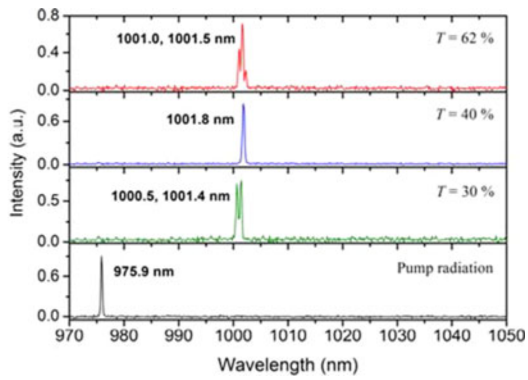


Fig. 6. Laser emission spectrum measured at $P_{abs} = 10.7$ W for different output couplings. The emission spectrum of pump radiation is also shown.

The pulse amplitude fluctuations were estimated as 10%, whereas the timing jitters amounted roughly to 5%. The output stability over a period of ten minutes was about ±3%, monitored at an output power of 0.84 W ($P_{abs} = 15.6$ W).

The pulsed laser action of the miniature Yb:$LuPO_4$ crystal rod, induced by a GaAs saturable absorber, was of a unique spectral feature: it occurred at very short wavelengths near 1002 nm, almost independent of either the pump level or the output coupling utilized (not lower than $T = 30\%$). Fig. 6 shows the emission spectrum for $T = 30\%$, 40%, and 62%, respectively, which was measured at $P_{abs} = 10.7$ W. One sees that upon changing the output coupling from $T = 30\%$ to $T = 62\%$, the emission wavelengths remained in a very narrow spectral range of 1000.5−1001.8 nm. The emission spectrum of the pump radiation is also presented in this figure, showing a center wavelength of 975.9 nm, with a bandwidth of about 0.3 nm. The quantum defect, defined as $\xi = 1 - \lambda_p/\lambda_l$ (λ_p: pump wavelength; λ_l: laser wavelength), which serves as a measure of the energy loss in converting a pump photon into a laser photon, is calculated as 2.6%. This value turns out to be the lowest among pulsed Yb-ion solid-state lasers that have been developed thus far under 976-nm diode pumping.

The pulsed laser emission at wavelengths near 1002 nm, which proved to be independent of the output coupling within the range from $T = 30\%$ to $T = 62\%$, is related to the strong emission band having its peak located exactly at 1002 nm, in the σ-polarized emission spectrum of Yb:$LuPO_4$ crystal [2]. The σ-polarized spectroscopic properties are responsible for the specific laser performance demonstrated in the current experiment, since the laser beam is propagated along the crystallographic c axis of Yb:$LuPO_4$ crystal. In order to gain more insight into the physical reasons

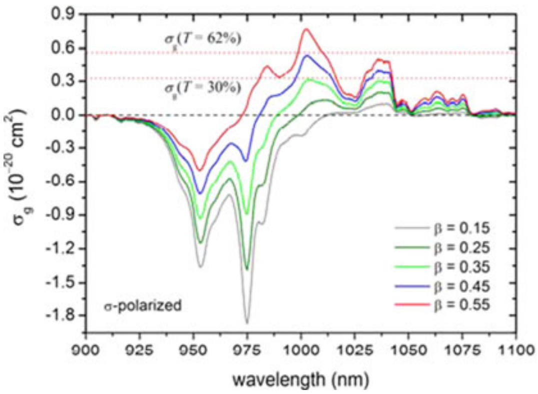


Fig. 7. Curves of σ-polarized gain cross-section for Yb:$LuPO_4$ crystal, calculated for a number of excitation levels ranging from $\beta = 0.15$ to $\beta = 0.55$.

for the output-coupling-independent laser emission at 1002 nm, we made a calculation of the gain cross-section as a function of emission wavelength, $\sigma_g(\lambda) = \beta\sigma_{em}(\lambda) - (1-\beta)\sigma_{abs}(\lambda)$, by use of the σ-polarized absorption and emission spectra of Yb:$LuPO_4$ crystal [2]. In this expression, β is the fraction of Yb-ions that have been excited to the upper manifold ($^2F_{5/2}$); whereas σ_{em} and σ_{abs} are, respectively, the emission and absorption cross-sections. As is known, for a quasi-three-level laser like an Yb-ion one, the laser action, in the absence of any internal wavelength selecting element, will occur at those wavelengths where the gain cross-section, and hence the net gain, reaches its maximum. For the pulsed laser to arrive at threshold, its gain must be able to compensate for the overall losses of the resonator, viz., the gain cross section must satisfy the relation [11], $2\sigma_g N_t l = -2\ln(1-L_i) - 2\ln(T_0) - \ln(1-T)$. In this relation, N_t is the Yb-ion concentration; l the length of the Yb:$LuPO_4$ crystal rod; T_0 the initial transmission of the GaAs plate; T the output coupling; and L_i the total internal losses.

Fig. 7 depicts the curves of $\sigma_g(\lambda)$ over a wavelength range of 900−1100 nm, for a number of values for β ranging from 0.15 to 0.55. It is seen that at lower excitation levels, the highest gain occurs within the emission band around 1037 nm; starting from $\beta = 0.35$ it will shift to the short-wavelength band that is peaked at about 1002 nm. According to the threshold lasing condition given above, the amount of σ_g required for reaching laser threshold, can be estimated for a specific output coupling, providing the value for L_i is given. For the current miniature Yb:$LuPO_4$ crystal rod laser, the overall internal losses are assumed to be $L_i = 0.10$, which include the transmission of the plane reflector at 1002 nm (≈0.015), the scattering or other dissipative losses in the Yb:$LuPO_4$ as well as in the GaAs crystal, and the residual Fresnel reflection loss of the uncoated laser rod (the etalon effect may partly diminish such reflection). The numbers for other parameters involved are: $N_t = 6.15 \times 10^{20}\,cm^{-3}$; $l = 0.2\,cm$, $T_0 = 0.90$ (the actual measured value). One then obtains $\sigma_g = 0.315$ for $T = 30\%$; $\sigma_g = 0.564$ for $T = 62\%$, which are also marked in Fig. 7. One notices that the threshold gain, required by the laser under conditions of $T = 30\%$, coincides approximately with the curve for $\beta = 0.35$; while the gain for an output coupling of $T = 62\%$ is slightly higher than that at an excitation level of $\beta = 0.45$. These results suggest that the pulsed laser action, to be achieved with an output coupling greater than $T = 30\%$, will occur at wavelengths of about 1002 nm. This agrees with the experimental results.

4. Conclusion

In summary, pulsed laser oscillation at 1002 nm was achieved with a miniature Yb:$LuPO_4$ crystal rod longitudinally pumped by a 976-nm diode laser, with a GaAs plate acting as saturable absorber. With 17.2 W of pump power absorbed, 0.85 W of pulsed output power was generated at a pulse repetition rate of 3.7 kHz, with a quantum defect amounting only to 2.6%; the resulting pulse energy, duration, and peak power being, respectively, 230 μJ, 5.5 ns, and 41.8 kW. Among the compact pulsed Yb- and Nd-ion solid-state lasers operating in the 1.0−1.1 μm spectral region that have been developed thus far, the oscillation wavelength achieved here represents the shortest; while the quantum defect proves to be the lowest. Given the promising pulsed laser performance demonstrated in the present work, one can expect further improvement to be made in scaling the pulsed output power; in increasing the pulse energy; and in reducing the pulse duration, through optimizations of resonator configuration, thickness of the GaAs crystal plate, and parameters of the $Yb:LuPO_4$ crystal.

References

[1] W. F. Krupke, "Ytterbium solid-state lasers: The first decade," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 1287–1296, Nov./Dec. 2000.

[2] J. Liu *et al.*, "Spectroscopic properties and continuous-wave laser operation of $Yb:LuPO_4$ crystal," *Opt. Lett.*, vol. 39, no. 20, pp. 5881–5884, 2014.

[3] L. D. Deloach, S. A. Payne, L. L. Chase, L. K. Smith, W. L. Kway, and W. F. Krupke, "Evaluation of absorption and emission properties of Yb^{3+} doped crystals for laser applications," *IEEE J. Quantum Electron.*, vol. 29, no. 4, pp. 1179–1191, Apr. 1993.

[4] L. A. Boatner, "Synthesis, structure, and properties of monazite, pretulite, xenotime," *Rev. Miner. Geochem.*, vol. 48, no. 1, pp. 87–121, 2002.

[5] J. Liu, X. Chen, W. Han, D. Zhong, S. Zhang, and B. Teng, "Columnar crystal of $Yb:LuPO_4$ for high-power miniature rod lasers," *Opt. Mater. Exp.*, vol. 5, no. 11, pp. 2437–2442, 2015.

[6] L. Wang *et al.*, "Repetitively Q-switched laser operation of miniature $Yb:LuPO_4$ crystal rod," *Opt. Mater. Exp.*, vol. 7, no. 3, pp. 1048–1054, 2017.

[7] L. Wang, W. Han, H. Xu, D. Zhong, B. Teng, and J. Liu, "Passively Q-switched oscillation at 1005–1012 nm of a miniature $Yb:LuPO_4$ crystal rod laser," *Laser Phys. Lett.*, vol. 14, p. 045807, 2017.

[8] A. L. Smirl, G. C. Valley, K. M. Bohnert, and T. F. Boggess, "Picosecond photorefractive and free-carrier transient energy transfer in GaAs at 1 μm," *IEEE J. Quantum Electron.*, vol. 24, no. 2, pp. 289–303, Feb. 1988.

[9] G. C. Valley and A. L. Smirl, "Theory of transient energy transfer in gallium arsenide," *IEEE J. Quantum Electron.*, vol. 24, no. 2, pp. 304–310, Feb. 1988.

[10] P. Silverberg, P. Omling, and L. Samuelson, "Hole photoionization cross sections of EL2 in GaAs," *Appl. Phys. Lett.*, vol. 52, no. 20, pp. 1689–1691, 1988.

[11] O. Svelto, *Principles of Lasers*. New York, NY, USA: Springer, 2010, ch. 7.