PACS numbers: 42.65.Ky; 42.55.Rz; 42.55.Xi
DOI: 10.1070/QE2004v034n10ABEH002796

Efficient frequency doubling in a transversely diode-pumped Nd : YAG laser

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***Abstract*. A simple scheme is proposed for efficient frequency doubling in a Nd : YAG laser transversely pumped by diode lasers. The average output TEM_{00}-mode power of the 1064-nm *Q*-switched laser at the *Q*-switching rate exceeding 20 kHz is 15 W. The radiation power at the second harmonic frequency ($\lambda = 532$ nm) is found to be 12 and 8.3 W for KTP and LBO crystals for *Q*-switching rates $f \geqslant 20$ kHz and 10 kHz, respectively. The maximum second-harmonic conversion efficiency is ~ 80 %.**

Keywords: *diode laser, Nd : YAG laser, transverse pumping, Q-switching, nonlinear crystal, frequency doubling.*

1. Introduction

Modern solid-state lasers are pumped by high-power diode lasers (DLs), which can be used for longitudinal and transverse pumping. Longitudinally pumped solid-state lasers are more efficient and emit high-quality beams ($M^2 \sim 1$) [1, 2]. However, it is quite difficult to obtain high output powers upon longitudional pumping. Lasers with transverse pumping of the active medium are conventionally used to achieve an output power of 100 W or more (see, for example, [3 – 5]). However, the efficiency of these lasers is lower and considerable difficulties are encountered in obtaining radiation beam with $M^2 \sim 1$.

In this paper, we report on a simple design of an Nd : YAG laser with a transverse DL pumping and an average output power of 15 W, which operates in the TEM_{00} mode, as well as on efficient frequency doubling of laser radiation ($\lambda = 532$ nm) with an output power of 12 W.

2. Experiment and characteristics of the Nd : YAG laser

The experimental setup of a laser with a four-mirror Z-shaped resonator is shown in Fig. 1a. The reflectivity r of mirrors (*1*)–(*4*) at $\lambda = 1064$ nm was more than 99.5 %. Mirror (*4*) was dichroic and had $r > 99.5$ % at $\lambda = 532$ nm. The transmission coefficient τ of mirror (*3*) at this wavelength was 92 %. A nonlinear crystal (BBO, KTP or LBO) was placed at the waist of the resonator between spherical mirrors (*3*) and (*4*) (with radii of curvature $R = 200$ and 150 mm, respectively) for obtaining the second-harmonic radiation. The beam diameter at the waist was 100 – 150 μm. To obtain the highest output power at $\lambda = 1064$ nm, mirror (*1*) was replaced by a mirror with an optimal transmission coefficient, and the nonlinear crystal was removed from the resonator.

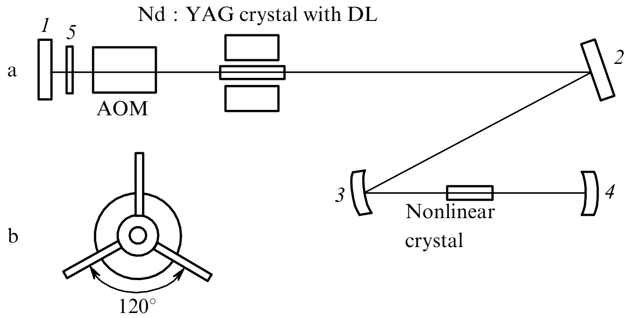

Figure 1. Scheme (a) and pump geometry (b) of an Nd : YAG laser: (*1*–*4*) resonator mirrors; (*5*) quarter-wave plate.

A Nd : YAG crystal with a mass concentration of [Nd] = 1 %, diameter 2 mm and length 63 mm was used as the active medium. The crystal was illuminated from three sides by Derringer-type DL arrays manufactured by IMCLaser (USA) and emitting at a wavelength $\lambda_p = 808$ nm (Fig. 1b). The laser was cooled by distilled water circulating in a closed-cycle cooler that ensured a temperature stabilisation to within 0.1 °C. The working temperature of the laser was 23 °C and could be controlled over a wide range. An MZ-305 acousto-optic modulator (AOM) was used for *Q*-switching. The *Q*-switch with a carrier frequency of 50 MHz was made of a quartz crystal and cooled by circulating water. Quarter-wave plate (*5*) was used to compensate for the induced birefringence.

The laser cavity was calculated by using matrix technique on a computer and was optimised by taking into account the thermal lens in the active medium and the dispersion of the air gap between the nonlinear crystal and mirror (*4*). We also estimated the diffraction loss in the

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Received 18 May 2004; revision received 15 July 2004
Kvantovaya Elektronika **34** (10) 930 – 932 (2004)
Translated by Ram Wadhwa

TEM_{00} mode ($\sim 10\,\%$) and higher-order modes, e.g., TEM_{01} ($\sim 50\,\%$).

The following considerations formed the basis for choosing the optimal size of the most efficient active medium. Pumping of the active element induces birefringence in it, leading to depolarisation of radiation passing through the crystal and to an increase in the losses. Depolarisation losses are proportional to w^4, while the energy extraction (and hence the output power) is proportional to w^2 (w is the 'size' of the TEM_{00} mode in the active element). This means that an optimal value of w exists for the fundamental resonator mode. Estimates of the optimal value of w (~ 1 mm) under the conditions of our experiments are given in [6]. In this case, the diameter of the rod for an efficient energy extraction should be about 2 mm.

Figure 2 shows the dependence of the laser output power P_{out} at $\lambda = 1064$ nm (for an AOM modulation frequency $f = 20$ kHz) on the DL current, as well as on the emitted light power P_{light} and the consumed electric power P_{elec} of the DL. The saturation of the output power by the pump current is due to mismatching of the resonator caused by thermo-optical effects. The focal length of the thermal lens in the active element for saturation currents was ~ 25 cm, and the electric power efficiency was 5 %, while the light power efficiency was 12.5 % (the differential efficiencies were 10 % and 21 %, respectively). This dependence was obtained by using output mirror (*1*) (see Fig. 1) with an optimal transmission coefficient $\tau = 20\,\%$. Lasing under these conditions occurred in the TEM_{00} mode. Figure 3 shows the dependence of the output power and the lasing pulse duration τ on the modulation frequency f. The pulse duration was measured by an LFD-2 avalanche photodiode with a time constant < 1 ns.

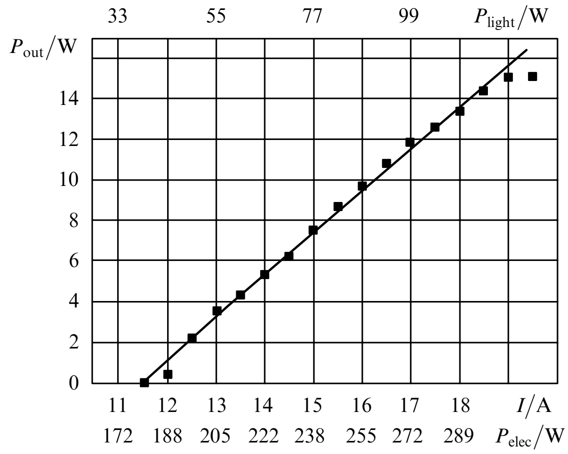

Figure 2. Dependence of the 1064-nm output power on the current, output power and the consumed electric power of the DL.

3. Frequency doubling of laser radiation

Because the main purpose of our study is to develop a source with a beam divergence close to the diffraction-limited divergence in the region of 532 nm, we consider the frequency doubling effect in greater detail. It is well known [7] that the losses introduced by a nonlinear crystal in the case of intracavity frequency doubling of laser radiation must be equal to the losses introduced by the optimal

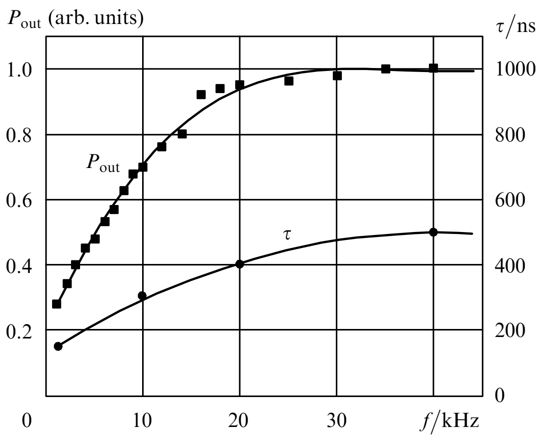

Figure 3. Dependence of the output power at $\lambda = 1064$ nm and the laser pulse duration on the modulation frequency of an AOM.

output mirror of the laser without a nonlinear crystal. This is a necessary condition for attaining maximum output power at the doubled frequency. The latter circumstance must be taken into account especially in the case of intracavity frequency doubling in cw lasers because unlike repetitively pulsed lasers, it is impossible to optimise the operation of cw lasers when a nonlinear crystal has been chosen incorrectly.

The second-harmonic power was calculated numerically for choosing the nonlinear crystals suitable for second-harmonic generation and for determining their optimal parameters, including the length L_{cr}. Calculations were made by using a system of truncated equations for real electric field amplitudes, derived from the wave equation by the method of slowly varying amplitudes in weakly absorbing and weakly nonlinear medium in the plane-wave approximation. These equations were solved by using software specially developed for determining the required parameters of nonlinear crystals even in the case of deviation from the exact phase-matching condition.

A simple difference scheme was used, in the particular case of second harmonic generation when the effect with the normalised phase $\Psi = \Delta kz + \pi/2$ accumulates most rapidly, for numerically solving the following system of equations [8] under the initial conditions $z = 0$, $a_2(0) = 0$:

$$\frac{\partial a_1}{\partial z} = -\sigma_1 a_1 a_2 \cos(\Delta kz),$$

$$\frac{\partial a_2}{\partial z} = \sigma_2 a_1^2 \cos(\Delta kz).$$

In the case of exact phase matching (for a wave detuning $\Delta k = 2k_1 - k_2 = 0$), the system has an exact analytic solution:

$$a_2(z) = a_{10}\left(\frac{\sigma_2}{\sigma_1}\right)^{1/2} \tanh[(\sigma_1\sigma_2)^{1/2} a_{10} z].$$

Here $\sigma_1 = 4\pi^2 d_{eff}/\lambda_1 n_1$ and $\sigma_2 = 2\pi^2 d_{eff}/\lambda_2 n_2$ are the nonlinear coupling coefficients; d_{eff} is the effective nonlinearity; λ_i is the wavelength; n_i is the refractive index; k_i is the wave vector; a_i is the electric field amplitude; a_{10} is the initial amplitude of the electric field of the fundamental radiation;

z is the running coordinate; and c is the velocity of light in vacuum.

Calculations were made by using expressions and data for computing the effective nonlinearity d_{eff}, as well as the Sellmeyer equations for determining the refractive indices n_i [9–12]. Standard formulas (see, for example, [8]) were used for calculating the phase-matching angles in the fundamental radiation wavelength range 1.07–0.75 μm. Calculations were performed for LBO, KTP and BBO nonlinear crystals. Figure 4 shows the calculated dependences of the second-harmonic power density S_2 on the length of the crystals. The fundamental input radiation power density $S_1(0)$ was taken equal to 150 MW cm^{-2}, which corresponds to a modulation frequency of 10–15 kHz. The radiation power density was defined as $S_i = cn_i a_i^2/8\pi$, $i = 1, 2$. The approximate optimal crystal lengths for obtaining a second-harmonic radiation output power are as follows: $\sim$ 10 mm (LBO, ooe phase matching), $\sim$ 2 mm (KTP, eoe phase matching) and $\sim$ 5 mm (BBO, ooe phase matching).

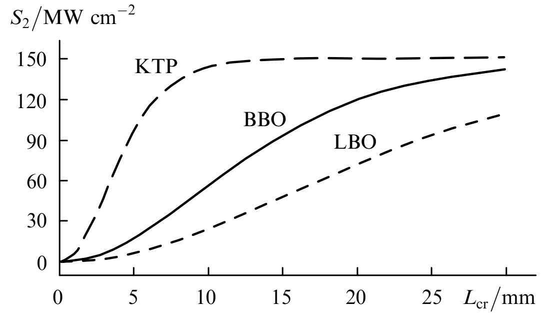

Figure 4. Calculated dependences of the second-harmonic power densities S_2 on the crystal length.

The walk-off angle was calculated from the expression

$$\tan\beta_i = \frac{\left[1-(n_{\text{o}}/n_{\text{e}})^2\right]\tan\theta}{1+(n_{\text{o}}/n_{\text{e}})^2\tan^2\theta},$$

where θ is the phase-matching angle. Numerical estimates of the angular and spectral acceptance bandwidths could be obtained by using the same software.

We studied the second-harmonic generation using crystals of BBO (ooe phase matching, $\theta = 22.8°$, $\varphi = 90°$, 5 mm), KTP (eoe phase matching, $\theta = 90°$, $\varphi = 23.5°$, 5 mm) and LBO (ooe phase matching, $\theta = 90°$, $\varphi = 11.6°$, 12 mm). All nonlinear elements had 'two-hump' antireflection coatings at working wavelengths with $r < 0.5\,\%$. The following maximum powers were obtained: BBO (5 W, $f = 15$ kHz); KTP (12 W, $f > 20$ kHz); LBO (8.3 W, $f = 10$ kHz). Note that the maximum power for BBO was limited by the damage of the coating. Figure 5 shows a typical dependence of the second-harmonic power on the DL current for an LBO crystal ($f = 10$ kHz). One can see that this dependence is quadratic at the initial stage, but levels out subsequently due to mismatching of the resonator caused by thermo-optical effects. The dependence of the output power on the modulation frequency for the LBO crystal has a maximum at a frequency of 10 kHz.

The frequency dependence of the output power for a KTP crystal increases monotonically up to $f = 20$ kHz, and remains constant efficiency in the interval 20–40 kHz. The second-harmonic conversion efficiency for KTP was 80 %.

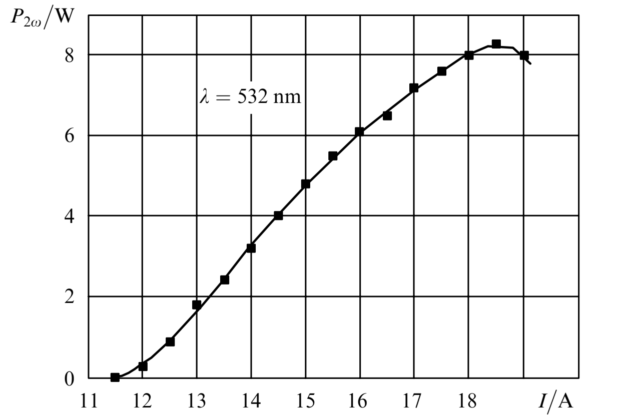

Figure 5. Dependence of the second-harmonic output power on the DL current I for an LBO crystal at $f = 10$ kHz.

Considering that the maximum second-harmonic power for LBO was achieved at a frequency of 10 kHz, which corresponds to an output power of 10.5 W at $\lambda = 1064$ nm (see Fig. 3), the second-harmonic conversion efficiency for this crystal was 79 %.

Thus, we have developed a low-power-consuming laser with a high second-harmonic conversion efficiency. The results raise hopes of obtaining an efficient radiation source at 532 nm with an output power of $\sim$ 100 W and higher in the TEM_{00} mode.

References

1. Tidewell S.C., Seamans J.F., Bowers M.S., Cousins A.K. *IEEE J. Quantum Electron.*, **28**, 997 (1992).
2. Tsunekane M., Taguchi N., Inaba H. *Appl. Opt.*, **37**, 3290 (1998).
3. Ostermeyer M., Klemz G., Kubina P., Menzer R. *Appl. Opt.*, **41**, 7573 (2002).
4. Fujikawa S., Furuta K., Yasui K. *Opt. Lett.*, **26**, 602 (2001).
5. Lee S., Yun M., Cha B.H., Kim C.J., Suk S., Kim H.S. *Appl. Opt.*, **41**, 5625 (2002).
6. Bykov V.P., Silichev O.O. *Lazernye rezonatory* (Laser Resonators) (Moscow: Fizmatlit, 2003) p. 211.
7. Smith R.G. *IEEE J. Quantum Electron.*, **6**, 215 (1970).
8. Dmitriev V.G., Tarasov L.V. *Prikladnaya nelineinaya optika: Generatory vtoroi garmoniki i parametricheskie generatory sveta* (Applied Nonlinear Optics: Second Harmonic Generators and Optical Parametric Oscillators) (Moscow: Radio i Svyaz', 1982) pp 45–57.
9. Kato K. *IEEE J. Quantum Electron.*, **26**, 1173 (1990).
10. Lin S., Sun Z., Wu B., Chen C. *J. Appl. Phys.*, **67**, 634 (1990).
11. Dmitriev V.G., Nikogosyan D.N. *Opt. Commun.*, **95**, 173 (1993).
12. Dmitriev V.G., Gurzadyan G.G., Nikogosyan D.N. *Handbook of Nonlinear Optical Crystals* (Berlin: Springer-Verlag, 1996; Moscow: Radio i Svyaz', 1991).