

PACS numbers: 42.65.Ky; 42.70.Mp
DOI: 10.1070/QE2001v031n07ABEH002020

Doubling microsecond single pulses in a KTP crystal

S A Abrosimov, S G Grechin, D G Kochiev, N Yu Maklakova, V N Semenenko

***Abstract*. The 90° phase-matching SHG is performed for microsecond single pulses from a Nd^{3+} : YAP laser in a KTP crystal with the 29 % conversion efficiency. The 90° phase-matching temperature is 54 °C. The crystal surface damage threshold measured without and with an antireflection coating was 107 ± 11 and 40 ± 4 J cm^{-2}, respectively.**

Keywords: *KTP crystal, damage threshold, second harmonic generation, conversion efficiency.*

1. Introduction

At present the efficiency of doubling nanosecond radiation pulses from lasers emitting in the micron range is studied in detail and the high SHG efficiency has been achieved. For example, the SHG efficiency for 8-ns single pulses from Nd^{3+} : YAG in a KTP crystal amounts to 80 % [1]. However, frequency conversion of microsecond pulses has not been adequately investigated, although doubling microsecond pulses is important in practice, for example, for laser lithotrypsy [2, 3].

In this paper, we study theoretically and experimentally the possibility of building a highly efficient frequency doubler for microsecond laser single pulses.

2. Conversion optimisation

To achieve the efficient frequency conversion of radiation with the power density below 1.0 MW cm^{-2}, the radiation should be focused into a nonlinear crystal. At focusing angles equal to several degrees, the 90° phase matching should be realised. To solve this problem, one should choose the radiation wavelength, the type of a nonlinear crystal and its length, as well as the focal distance of a lens.

S A Abrosimov, D G Kochiev General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: abr@kapella.gpi.ru
S G Grechin Research Institute of Radio Electronics and Laser Technique, N E Bauman Moscow State Technical University, 2-ya Baumanskaya ul. 5, 107005 Moscow, Russia; e-mail: gera@mx.bmstu.ru
N Yu Maklakova, V N Semenenko Institute of Mineralogy and Petrography, Siberian Division, Russian Academy of Sciences, ul. acad. Koptyuga 3, 630090 Novosibirsk, Russia; e-mail: ssc@online.ru

Received 29 January 2001; revision received 17 April 200
Kvantovaya Elektronika **31** (7) 643 – 646 (2001)
Translated by M N Sapozhnikov

The 90° phase matching at the wavelength 1064.2 nm of a Nd^{3+} : YAG laser can be obtained in two crystals, $Ba_2NaNb_5O_{15}$ and $LiNbO_3$. At the wavelength 1079.6 nm of a Nd^{3+} : YAP laser, the noncritical phase matching can be achieved, except the above crystals, in a KTP crystal (noncritical in both angles). The angular phase-matching width of all these crystals is approximately the same, but a narrow temperature phase-matching width and a low radiation resistance of $Ba_2NaNb_5O_{15}$ and $LiNbO_3$ crystals make the use of a KTP crystal preferable.

To obtain the maximum conversion efficiency, the length of a nonlinear crystal and the focusing angle of radiation should be optimised. The radiation power density should not exceed the damage threshold of a doubling crystal.

The phase-matching direction in a KTP crystal at room temperature at the emission wavelength of a Nd^{3+} : YAP laser lies in the xz plane at the angle $\theta = 85 - 88°$ to the crystal axis (for crystals grown by different methods). The phase matching along the x axis is achieved by crystal heating. In this case, the phase matching is noncritical in both angles and has the maximum angular width $2\Delta\varphi = 12° \, cm^{1/2}$, $2\Delta\theta = 4.5° \, cm^{1/2}$. The temperature phase-matching width is $2\Delta T = 17.5$ °C. The temperature of crystal heating required for obtaining 90° phase matching is 153 °C according to Ref. [4] and 63 °C according to Ref. [5].

The SHG for focused Gaussian beams was considered in the fixed-field approximation in Ref. [6]. The equations were obtained assuming that the focusing angle is much smaller than the angular phase-matching width and all the spatial radiation components have the same wave mismatch. The expression obtained in Ref. [6] represents a product of two groups of parameters, one of which takes into account the rise of the radiation power due to coherent accumulation of the second harmonic radiation, while the second one takes into account a change in the radiation power density over the nonlinear crystal length (the aperture function).

In the general case, similarly to Ref. [6], the conversion efficiency η can be represented as a product of three factors: the coefficient η_n taking into account coherent accumulation of collimated radiation over the interaction length, the coefficient η_r describing the ratio of the radiation divergence to the angular phase-matching width, and the coefficient η_p taking into account a change in the radiation power density over the crystal length:

$$\eta = \eta_n \eta_r \eta_p. \quad (1)$$

In the case of 90° phase matching over both angular coordinates, the displacement of the beams and the wave detuning are absent. In this case, the aperture function from

Ref. [6] has the analytic form

$$\eta_p = \arctan^2(\xi)/\xi^2, \quad (2)$$

where ξ is the parameter of radiation focusing. Hereafter, we use the notation from Refs [6, 7]. It follows from (2) that for $\xi < 0.1$ in the case under study, a change in the power density over the crystal length can be neglected.

The influence of the radiation divergence (of the focusing angle) in the problem under study can be taken into account with the help of the expression

$$\eta_r = \frac{\int_{-\pi}^{\pi}\int_{-\pi}^{\pi} F(\varphi,\theta)\mathrm{sinc}^2\left\{0.443\pi\left[(\varphi/\Delta\varphi)^2 - (\theta/\Delta\theta)^2\right]\right\}\mathrm{d}\varphi\mathrm{d}\theta}{\int_{-\pi}^{\pi}\int_{-\pi}^{\pi} F(\varphi,\theta)\mathrm{d}\varphi\mathrm{d}\theta}, \quad (3)$$

where $F(\varphi, \theta)$ is the angular distribution of the radiation intensity.

The dependences of $\eta_r\eta_p$ on the KTP crystal length for different focusing angles ψ are shown in Fig. 1. Of all the mechanisms considered here, the shortening of the interaction length is the main factor that reduces the conversion efficiency.

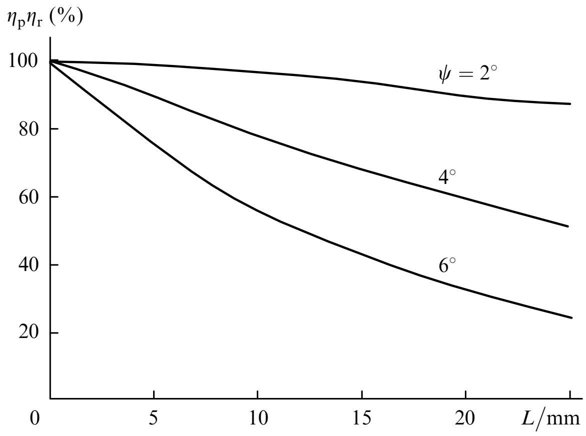

Figure 1. Dependences of $\eta_r\eta_p$ on the crystal length L for different angles of radiation focusing.

The conversion efficiency for a collimated beam (in the waist) is

$$\eta_n = \frac{\iiint I_{10}(x,y,t)\tanh^2\left\{\pi d_{\mathrm{eff}} L_{\mathrm{cr}}\left[I_{10}(x,y,t)/n^3\right]^{1/2}/\lambda_{10}\right\}\mathrm{d}x\mathrm{d}y\mathrm{d}t}{\iiint I_{10}(x,y,t)\mathrm{d}x\mathrm{d}y\mathrm{d}t}, \quad (4)$$

where $I_{10}(x,y,t)$ is the incident fundamental radiation intensity; d_{eff} is the effective nonlinearity coefficient; L_{cr} is the length of a nonlinear crystal; n is the refractive index of the crystal; λ_{10} is the fundamental radiation wavelength in free space.

Fig. 2 shows the dependences of the conversion efficiency η on the crystal length for different focusing angles ψ provided by different focusing systems at a fixed laser-pulse energy of 175 mJ and a pulse duration of 900 ns. We used in our calculations the coefficients of the nonlinear susceptibility tensor from Ref. [8]. At $\psi = 2°$, the high conversion efficiency cannot be obtained because of a low radiation power density. At $\psi = 6°$, the low conversion efficiency caused by limitations imposed by mechanisms (2) and (3). In addition, at $\psi = 6°$ in the case under study, the radiation power density is approximately 40 J cm^{-2}, which is, as shown below, is comparable with the crystal damage threshold.

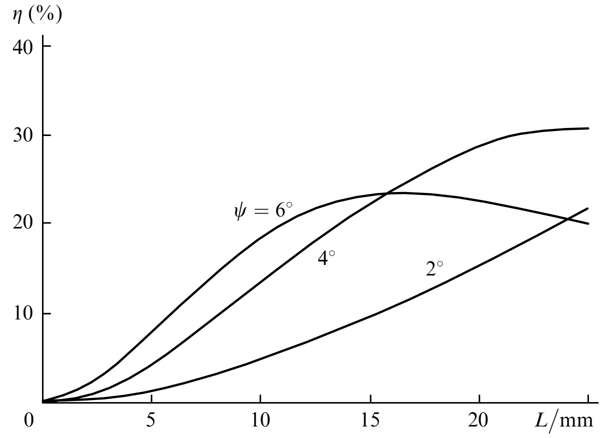

Figure 2. Dependences of the second harmonic energy η on the crystal length L for different angles of radiation focusing.

3. Experimental studies

We used in our experiments actively Q-switched Nd^{3+}:YAP laser with a pulse duration of 900 ns, a pulse energy of 130 mJ, and a pulse repetition rate of 6 Hz. The fraction of depolarised output radiation did not exceed 3.8 %.

We measured the crystal damage threshold and the conversion efficiency. All the crystals studied were flux-grown at the Institute of Mineralogy and Petrology, Siberian Division, RAS (Novosibirsk).

No data about the damage threshold of a KTP crystal upon irradiation by microsecond pulses were available to us. According to Ref. [9], the damage threshold of this crystal was measured upon irradiation by 10 – 30-ns single pulses. The damage threshold of flux-grown KTP crystals irradiated by 30-ns, 1064.2-nm pulses was 330 MW cm^{-2} (10 J cm^{-2}) [10]. The damage threshold of hydrothermal crystals irradiated by laser pulses of the same duration was 150 MW cm^{-2} (4.5 J cm^{-2}) [11] and for 125-μs pulses the threshold was 1 MW cm^{-2} (125 J cm^{-2}) [12].

Because the laser that we used was not single-mode and single-frequency, we could not treat the damage threshold as a characteristic of the crystal material. We studied the resistance of the crystal to the laser radiation used in different applications. Because the damage of the output face of a crystal is usually caused by a combined action of the fundamental radiation and the second harmonic, we performed measurements for the total radiation (the second harmonic and the unconverted fundamental radiation). For this purpose, the laser radiation was converted to the second harmonic in a separate KTP crystal with a conversion efficiency of 20 %. The total radiation was focused on the front face of the KTP crystal under study (Fig. 3). The measurements were performed for two samples – without an antireflection coating and with a Ta_2O_5/SiO_2 antireflection coating. To improve the accuracy of measurements of the energy distribution, we constructed an enlarged image of the radiation spot in the plane B. The energy density at the fundamental wavelength and the second harmonic was measured independently by the method of interchangeable apertures, as in Ref. [13].

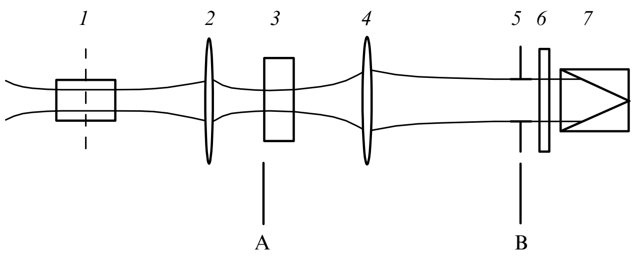

Figure 3. Optical scheme of measurements. (*1*) KTP crystal ($\theta = 90°$, $\varphi = 0$); (*2*, *4*) lenses; (*3*) KTP crystal under study; (*5*) interchangeable apertures; (*6*) filters; (*7*) IMO-2N calorimeter; (A) front-face plane of a sample; (B) image of plane A.

The distributions of the energy density for the fundamental radiation and the second harmonic on the input face A of the crystal under study with an antireflection coating are shown in Fig. 4. The damage threshold was defined as the energy density at which a spark was observed on the input face of the crystal within 2–3 s after the onset of irradiation. The damaged surface exhibited distinct circular indentations of diameter 50–100 μm. The size of indentations depended on the irradiation time. After prolonged irradiation for 60 s, the indentation diameter increased up to 500–1000 μm. The surface damage threshold measured upon simultaneous irradiation by the fundamental and second harmonics was 40 ± 4 J cm^{-2}.

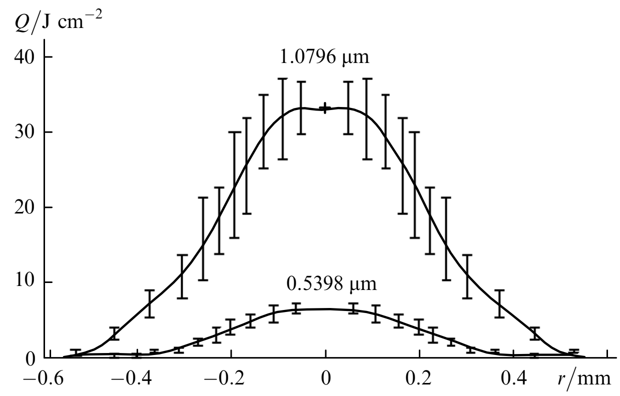

Figure 4. Distributions of the radiation energy density upon measurements of the damage threshold of a crystal with a Ta_2O_5/SiO_2 antireflection coating.

The surface damage threshold for the crystal without an antireflection coating, which was measured in a similar way upon simultaneous irradiation by the fundamental and second harmonics, was 107 ± 11 J cm^{-2}.

The conversion efficiency was measured for two samples of section 4 mm × 4 mm and length 15 and 20 mm. The phase-matching directions measured at room temperature lie in the xz plane and make angles 87.5 and 92.5° with the z axis. At the crystal temperature 54 °C, the 90° phase matching is realised, which is close to results obtained in Ref. [5]. The temperature obtained in Ref. [4] is obviously not typical for flux-grown crystals, because the method of crystal growth was optimised in Ref. [4] for obtaining high temperatures for 90° phase matching.

The maximum conversion efficiency for a 15-mm long KTP crystal was 20 % for the fundamental radiation energy of 173 mJ. The best results were obtained for a 20-mm long crystal, where the conversion efficiency was 29 % for the same pulse energy (173 mJ). The experimental dependence of the second-harmonic energy on the fundamental radiation energy is shown by points in Fig. 5. The solid curve is calculated by the method described above. The maximum energy density at the output face of the nonlinear crystal was 14.4 J cm^{-2}, which is substantially lower than the damage threshold. The KTP crystal worked in this regime for several hours. The results obtained above show that the SHG efficiency can be quite accurately calculated using the method described in this paper.

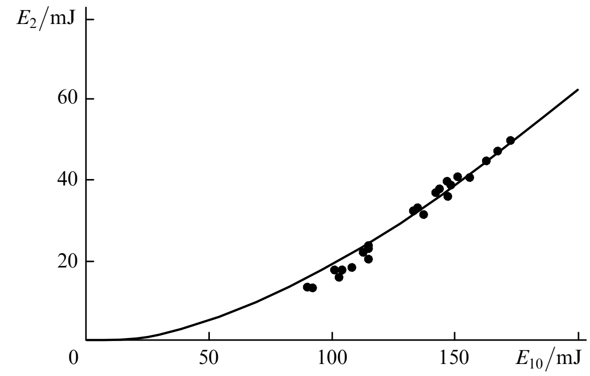

Figure 5. Dependence of the second harmonic energy on the fundamental radiation energy (points are experiment, the solid line is calculations).

4. Conclusions

We have demonstrated the 90° phase-matching SHG with the 29 % conversion efficiency in a 20-mm long KTP crystal irradiated by 1079.6-nm, 900-ns pulses from a Nd^{3+} : YAP laser. The 90° phase matching was realised at a temperature of 54°C. The surface damage threshold for the KTP crystal was 107 ± 11 J cm^{-2} without an antireflection coating and 40 ± 4 J cm^{-2} with the coating.

Acknowledgements. We used in the calculations the LID–SHG program packet (http://www.bmstu.ru/~lid).

References

1. Brown A J W, Bowers M S, Kangas K W, Fisher C H *Opt. Lett.* **17** 109 (1992)
2. Helfmann J, Mikhailov V A, Konov V I, Mueller G, Nikolaev D A, Pak S K, Sherbakov I A, Silenok A S *Proc. SPIE Int. Soc. Opt. Eng.* **1643** 78 (1992)
3. Mueller G, Helfmann J, Pashinin V P, Pashinin P P, Konov V I, Tumorin V V, Shklovsky E J *Proc. SPIE Int. Soc. Opt. Eng.* **2086** 103 (1993)
4. Garmash V M, Ermakov G A, Pavlova N I, Tarasov A V *Pis'ma Zh. Eksp. Teor. Fiz.* **12** 1222 (1986)

5. Ou Z Y, Pereira S F, Polzik E S, Kimble H J *Opt. Lett.* **17** 640 (1992)
6. Boyd J D, Kleinmann D A *J. Appl. Phys.* **39** 3597 (1968)
7. Dmitriev V G, Tarasov L V *Prikladnaya Nelineinaya Optika: Generatory Vtoroi Garmoniki i Parametericheskie Generatory Sveta* (Applied Nonlinear Optics: Second-Harmonic Oscillators and Parametric Oscillators) (Moscow: Radio I Svyaz', 1982)
8. Kato K *IEEE J. Quantum Electron.* **27** 1137 (1991)
9. Dmitriev V G, Gurzadyan G G, Nikogosyan D N *Handbook of Nonlinear Crystals* (Berlin: Springer, 1999)
10. Burnham R, Stolzenberger R A, Pinto A *IEEE Photon. Technol. Lett.* **1** 27 (1989)
11. Driscoll T A, Hoffman H J, Stone R E, Perkins P E *J. Opt. Soc. Am. B: Opt. Phys.* **3** 683 (1986)
12. Moody S E, Eggleston J M, Seamans J F *IEEE J. Quantum Electron.* **23** 335 (1987)
13. ISO/FDIS 11146 (1999(E)) 15