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# A microchip laser with intracavity second-harmonic generation

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***Abstract*. A short-pulse 'green' 532-nm $Nd^{3+}$ : $YVO_4$ and $KTiOPO_4$ microchip laser with intracavity second-harmonic generation, which is pumped by a 809-nm semiconductor laser diode, is developed.**

***Keywords***: *microchip laser, conversion of radiation into second harmonic.*

**1.** Microchip lasers are a promising subclass of solid-state diode-pumped lasers [1 – 3]. Their distinctive features are the low lasing threshold (a few milliwatts), the possibility of obtaining a single-frequency regime while preserving a high quality of radiation in combination with a simple design and small size ($\sim 1$ cm$^3$). Due to their parameters, microchip lasers are efficiently used in medical applications, optical detection and ranging, atmospheric probing and other technical fields. The aim of this work was to elaborate a short-pulse radiation source (down to subnanosecond pulse duration) operating at the second harmonic of the fundamental frequency, which would combine the laser and the second-harmonic converter in a single compact device.

As a base scheme, we chose a scheme with intracavity second-harmonic generation, which can provide a highly efficient conversion of pump radiation into green light and ensure significant output powers [1]. Lasers employing this optical scheme are characterised by the increased amplitude noise level, which appears due to stochastic energy redistribution among longitudinal modes participating in the nonlinear harmonic generation. Usually, to reduce the noise, many ($\sim 50$) longitudinal modes participating in the lasing are used, which allows one to smooth the noise and to obtain harmonic generation that is low-sensitive to intermode energy redistribution [3]. In this paper, we used an alternative method for obtaining single-mode lasing described in [4] which, in principle, allows one to completely eliminate the amplitude noise. The basic idea of this method is to use a short cavity of such a length that only one longitudinal mode could reach its gain contour. This leads to the main requirement to the active media material, i.e. a small width of the gain line.

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High bulk uniformity of the nonlinear element material is important for the efficient conversion into second harmonic, because the presence of nonuniformity prevents phase-matching condition along the entire crystal. Because the fulfillment of the condition $|\Delta kz| < \pi/2$ (where $\Delta k$ is the phase delay, $z$ is the nonlinear crystal length) is necessary for the efficient conversion, the acceptable fluctuations of the refractive index $\Delta n$ arising due to the material nonuniformity should satisfy the condition $\Delta n < \lambda/(4z)$. Thus, at $\lambda = 1$ μm and $z = 1$ cm, the tolerable fluctuations are $\Delta n < 2.5 \times 10^{-5}$. For the same reason, the uniformity of the temperature distribution along the crystal is also important. For the above estimate of $\Delta n$ and at acceptable temperature deviations $\Delta T \sim 0.5$ °C along the entire crystal, the condition $\mathrm{d}n/\mathrm{d}T < 5 \times 10^{-5}$ °C$^{-1}$ should be fulfilled.

As with any other nonlinear effect, the output power of harmonic generation should increase with increasing the intensity of radiation being converted. However, there are natural limitations to admissible intensity values which actually determine the power limit of a device. First, too high an intensity of laser radiation can damage a nonlinear crystal. Second, noticeable local changes in the refraction index can be caused by the low heat conduction of the crystal, due to which the phase-matching condition can be locally violated. Third, a decrease in the cross section of the incident beam during focusing, even in the case of collinear propagation of incident and converted beams, can result in a decrease in the area of effective interaction of the beams and in the mutual energy transfer between them, which is typical, for example, of anisotropic crystals. Because in an extraordinary wave the propagation directions of the phase and energy are different, even in the case of collinear initial and converted beams, their beam vectors prove to be noncollinear. As a result, the 'shift' of the converted beam from the initial one, which increases during the propagation of the converted beam through the nonlinear crystal, causes the decrease in the interaction region. This shift can be minimised if the beams propagate in the direction along which both the wave and the beam vectors are parallel to each other. During the second-harmonic generation in a single crystal, the above condition can be fulfilled in the plane perpendicular to the optical axis when the angular synchronism is noncritical. This type of synchronism can be realised in many crystals in a specified frequency range by changing temperature.

One should take into account that the conversion efficiency depends on the quality of the initial beam, while a multimode laser beam has a very nonuniform intensity distribution over its cross section. The small size of high-intensity areas both amplify the above-mentioned shift effect and decrease the dimension of the area of effective mutual energy transfer.

**2.** We used the $YVO_4 : Nd^{3+}$ crystal (the doping level was 1 %) as a laser active element (AE), because it has a large laser transition cross section, which enables obtaining short pulses in the single-pulse regime. The $KTiOPO_4$ (KTP) crystal was used for nonlinear conversion into second harmonic, while $Cr^{4+}$-doped garnet was employed as a passive gate (Fig. 1b).

The combined use of $YVO_4 : Nd^{3+}$ and garnet : $Cr^{4+}$ crystals entails two problems. First, it is impossible to obtain stable generation of sequential single pulses in a plain – parallel, or close to plane – parallel cavity. This is explained by the fact that the saturation energy density of $YVO_4 : Nd^{3+}$ at the working transition $Q_{sat} \approx 0.06$ J cm$^{-2}$ will be lower than that of the garnet : $Cr^{4+}$ crystal at the absorbing transition ($Q_{ab} = 0.08$ J cm$^{-2}$). Therefore, it is impossible to provide the radiation energy density necessary to open the passive gate made of a garnet : $Cr^{4+}$ crystal. This restriction can be lifted if, inside the cavity, the cross section of the generated beam inside the AE is larger than that inside the passive gate. Second, the $YVO_4 : Nd^{3+}$ crystal has high thermooptical sensitivity which, in the case of a high-power pumping and a temperature gradient in the crystal, would induce a thermal lens with a small focal length [5].

The first negative property of the $YVO_4 : Nd^{3+}$ – garnet : $Cr^{4+}$ pair can be compensated for by its second property. If the AE surface is in contact with a heatsinking substrate, then, when a large amount of heat is released in its internal region due to pumping, a substantial temperature gradient is established in the AE, thus forming a positive thermal lens. The latter significantly changes the properties of the cavity, which, being plane – parallel initially, becomes similar to a cavity with a spherical mirror. In such a cavity, the beam cross section on the spherical mirror (from the AE side) will be several times larger than that on the plane mirror (from the gate side). Thus, the absorption energy density in $YVO_4 : Nd^{3+}$ will be much lower than that in the garnet : $Cr^{4+}$ crystal, thereby making it possible to achieve the absorption energy density $Q_{ab}$ and to open fully the passive gate.

All the three crystals in the cavity were adjusted with each other and fixed in an aluminum housing (Fig. 1a). Nonlinear crystal (*2*) was inserted from above into horizontal groove in the housing and fixed with UV-hardened glue. Then, AE (*3*) and passive gate (*4*) are inserted into the vertical grooves from opposing sides of the housing and fixed with the same glue; in this case it is necessary to keep the cavity strictly plane – parallel. The KTP crystal is oriented at 45° with respect to stimulated-emission polarisation emerging from the AE; polarisation of the second-harmonic radiation will be rotated with respect to pump radiation polarisation also by 45°. The cavity mirrors were deposited directly on the external faces of the AE and the passive gate (Fig. 1b), the output mirror being highly reflecting and AR-coated at 1064 nm and at 532 nm, respectively. The total length of the laser cavity was 5 mm and the total volume was less than 1 cm$^3$.

Because the temperature regime is important for phase matching and to stabilise thermally the nonlinear crystal and to cool effectively the AE, the aluminum housing of the microchip laser was mounted on a Peltier heatsink. The crystal temperature was controlled with an NTC thermistor (a thermistor with a negative temperature coefficient), which was in contact with the housing. The current temperature of the crystals was monitored within the accuracy of 0.05 °C.

The AE was pumped by using a Unique Mode, UM 150020CB semiconductor cw laser diode. This laser diode produces a collimated beam, thereby enabling its subsequent focusing with a common spherical lens (we used the lens with the focal distance of 10 mm), without using special optics. This is important because in the case of longitudinal pumping, its efficiency is higher, the better coincide the shape and size of pump radiation spot with that of the longitudinal mode inside the cavity. Moreover, to get the fundamental transverse $TEM_{00}$ mode at the laser output, the pump radiation should have the beam waist diameter of less than 100 μm and no spherical aberrations.

The diode and its temperature were controlled with the LDD-9 laser diode driver and a Peltier element, respectively. The $YVO_4 : Nd^{3+}$ crystal absorbs radiation most efficiently at 809 nm. Our experiments have shown that the laser diode emits at this wavelength at temperature 28 °C. The max-

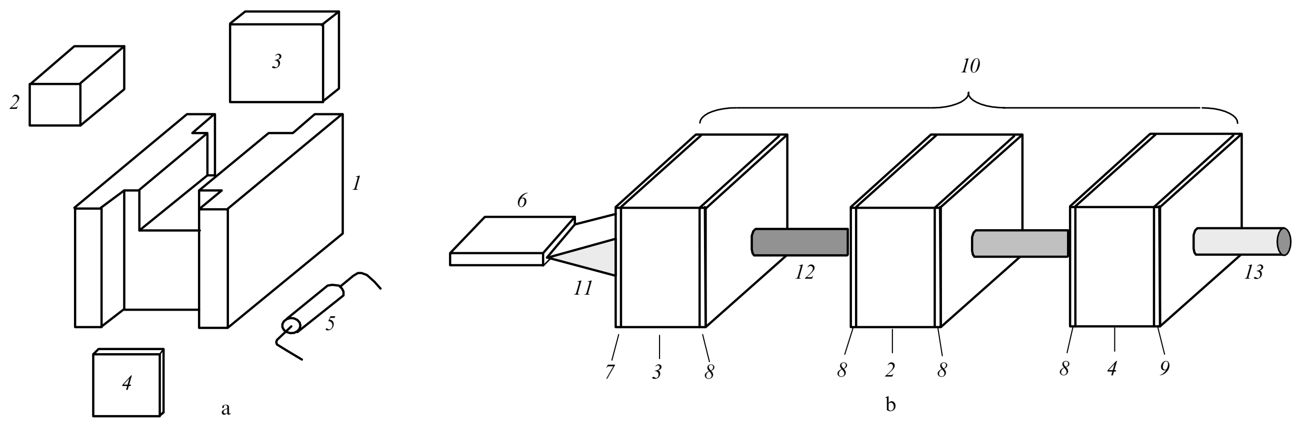


**Figure 1.** Components (a) and optical scheme (b) of the microchip laser: (*1*) aluminum housing; (*2*) nonlinear KTP crystal; (*3*) $YVO_4 : Nd^{3+}$ active element; (*4*) garnet : $Cr^{4+}$ passive gate; (*5*) thermistor; (*6*) pump laser diode; (*7*) AR@809, HR@1064 coating; (*8*) AR@1064@532 coatings; (*9*) AR@532, HR@1064 coating; (*10*) resonator; (*11*) pump radiation ($\lambda = 809$ nm); (*12*) laser radiation ($\lambda = 1064$ nm); (*13*) output radiation of the microchip laser ($\lambda = 532$ nm).

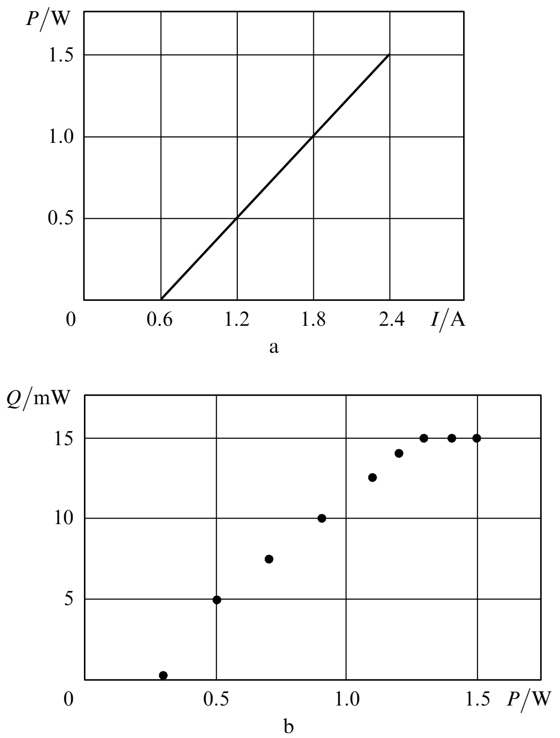


**Figure 2.** Experimental dependence of the output power $P$ of the pump laser diode on the current $I$, obtained at the diode active layer temperature of 28 °C (a), and the dependences of the average pulse power $Q$ of the microchip laser on the pump power $P$ (b).

imum output power of the diode was 1.5 W, which corresponded to the 2.4-A current through the p – n junction (Fig. 2a).

**3.** Stable lasing was obtained using this combined microchip laser emitting 532-nm, 1-ns, 0.75-μJ pulses at a pulse repetition rate of up to 20 kHz. Lasing was observed at the lowest transverse mode and at one longitudinal mode. The lasing threshold was 0.3 W.

Figure 2b shows the dependence of the average output power of the microchip laser on pump radiation power. One can see that the output power saturates near the pump power equal to 1.5 W. This saturation results from the formation of a thermal lens in the AE. When the pump power is increased while keeping the heat extraction constant, the focal distance of the thermal lens decreases, and the effective resonator configuration (i.e. the resonator taking into account the thermal lens) approaches a semi-concentrical one, thereby increasing diffractional losses in the cavity. Hence, the increase in the pump power only compensates for these losses. A further increase in the pump power should lead to a decrease in the output power of the microchip laser, because the losses would be increasing much faster. Lasing would terminate completely when the effective laser cavity becomes exactly equivalent to a semi-concentrical cavity, i.e. unstable one [5].

Figure 3 presents the oscillogram of the output pulse at 532 nm. Our experiments show that the shortest laser pulse duration is achieved for the temperature of the microchip laser housing equal to 20 °C and focusing of the pump radiation in the AE down to the depth of 100 μm.

When these values were deviated, the pulse duration increased, and the first pulse was followed immediately by the second pulse, radiation in that pulse being formed at another longitudinal mode. This can supposedly be explained as follows: until the first radiation pulse at the longitudinal mode (closest to the gain line centre) opens up the passive gate, the condition for second-mode generation is not yet fulfilled. The time during which the gate is open (4 μs) proves to be sufficient for the generation at the second mode to develop. Amplification at all other modes except for the central one is small, and they do not participate in the generation regime. Moreover, one can see from Fig. 3 that the trailing edge of the first pulse is stretched out. This is explained by the fact that lasing at 1064 nm is transformed into the second harmonic incompletely and continues to ‘travel’ in the cavity for a long time.

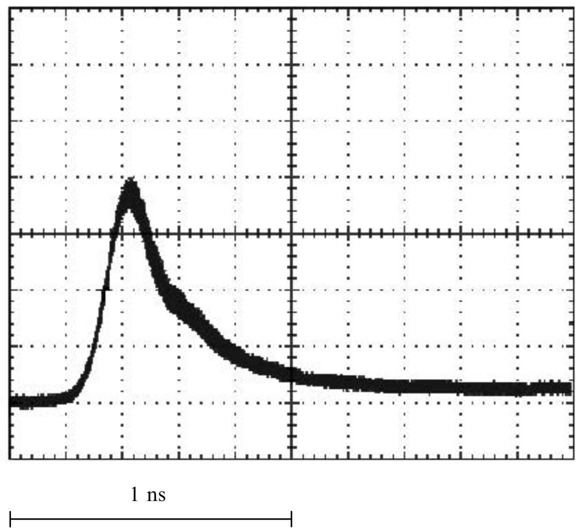


**Figure 3.** Oscillogram of the temporal profile of the output pulse of the microchip laser at $\lambda = 532$ nm.

In our experiments we studied the mode composition, power and shape of the output laser pulses at various positions of the AE with respect to the pump beam waist and various temperatures of the nonlinear crystal, which revealed another important feature. In the microchip laser under study, the AE can be fixed at various distances from the KTP crystal. Accordingly, the second-harmonic generation will take place in various regions on the KTP-crystal end faces. We noticed that when the border of such a region was located near the laser housing, the laser pulse parameters became very susceptible to changes in the housing temperature: to stabilise these parameters, the temperature fluctuations should be less than 0.05 °C. When, however, the border of the generation region was shifted towards the centre of the KTP crystal face, the pulse become significantly more stable: acceptable temperature fluctuations increased to 1 °C. This can be explained by intense heat fluctuations near the KTP surface which was in contact with the housing. Both heat deformations in KTP due to temperature fluctuations and the changes in the KTP refractive index caused local violations in the phase-matching conditions which, in turn, immediately affected the pulse profile. Therefore, we can conclude that optimisation of the employed scheme of intracavity conversion and, finally, the improvement of the quality of output pulses can be obtained not only by stabilising the temperature of the nonlinear crystal, but also by cooling efficiently the microchip laser as a whole.

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