Q-Switching and Frequency Doubling of Solid-State Lasers by a Single Intracavity KTP Crystal

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Abstract—The electrooptic characteristics of the KTP crystal are analyzed in detail and Q-switched operation of a diode-laser-pumped microchip Nd:YVO₄ laser is reported using an intracavity KTP crystal. The KTP was used also as a frequency-doubling crystal in type II phase matching for generating pulsed green beams. Low loss and high efficiency characteristics were realized by eliminating two components, i.e., a Q-switching or a frequency-doubling crystal and a polarizer, in comparison with the conventional frequency-doubling configuration. Up to 15.4-W peak output and 18-ns width green power was obtained with 760-mW pumping power on the Nd:YVO₄ microchip, which corresponded to 616 times enhancement of the CW output power.

I. INTRODUCTION

Diode lasers are efficient and reliable pump sources for solid-state lasers [1]. By matching the diode laser output wavelength to the particular dopant absorption of the solid state laser host, efficient laser oscillation can be realized. Intracavity frequency doubling of the diode laser pumped Nd³⁺ solid state lasers is an attractive technique for generating high power visible radiation [2]-[7]. There are several applications for compact blue-green sources, such as underwater communication, optical data storage and displays. At present, most schemes reported for generating blue-green beams are based on the frequency upconversion of near-infrared lasers with a nonlinear crystal.

Potassium titanyl phosphate (KTiOPO₄; KTP) is a relatively new material that has superior properties for several nonlinear optical applications and, in particular, for SHG (second-harmonic generation) or frequency doubling the 1-µm radiation of Nd lasers. Its low optical loss, high optical damage threshold, wide acceptance angle and thermally stable phase-matching properties make it useful for SHG. In addition, its large linear electrooptic r coefficients and low dielectric constants make it attractive for various electrooptic applications, such as modulators and Q-switches [8], [9]-[11]. To date no effort has been reported to use the KTP crystal simultaneously as a Q-switch and a SHG device.

We report a novel method for the Q-switching and frequency doubling of the Nd :YVO₄ laser. In this scheme a single KTP crystal was used both as a linear electrooptic material for the Q-switch of the fundamental beam and a nonlinear device for intracavity frequency doubling. The intense peak

fundamental power obtained by the Q-switching significantly enhances the green light output from the Nd:YVO₄ laser through the second-harmonic conversion process. We obtained a peak green power exceeding 15.4 W with CW pump power of 760 mW, which is 616 times enhancement in comparison to a green output power of 25 mW under CW

II. ELECTROOPTIC CHARACTERISTICS OF KTP

KTP is a biaxial nonlinear optical crystal that belongs to the rhombic mm-2 system. When it is used for type II SHG phase matching, the effective nonlinearity coefficient is about 10 times larger than that of KDP and its walk-off angle is small (~1 mrad).

In type II phase matching, the phase of the polarized wave caused by the electric field components of the fundamental wave in the f (fast) and s (slow) axis directions agrees with the phase of the SH (second-harmonic) wave in the f-axis direction. The transmitted fundamental wave has the electric field components in the s- and f-axis directions and both components have different phases, which result in an elliptically polarized beam. In the intracavity frequency doubling method, which uses a polarizer in the cavity of the Q-switched laser, the optical loss is induced by the polarizer due to this birefringent effect.

To illustrate this phenomenon, the polarization characteristic of an intracavity frequency doubled laser is shown in Fig. 1. When the fundamental wave is transmitted through the KTP crystal for type II phase matching, the second-harmonic wave is generated. The fundamental wave is reflected by the output coupling mirror and retransmitted through the KTP crystal, becomes an elliptically polarized wave, and thus the depolarized component is eliminated by the polarizer. To avoid this loss, the fundamental wave polarization was controlled by adjusting properly the optical axis angle in the KTP crystal [12].

This paper describes a method that controls the fundamental wave polarization by the electrooptic effect of the KTP crystal while maintaining the SHG phase matching condition. First, the refractive index of the KTP crystal for Nd :YVO₄ or
Nd:YAG fundamental laser beam at 1.064-μm wavelength is discussed [10], [12].

As illustrated in the Appendix, we find the principal axes of the new ellipsoid coincide with the original principal axes of the zero applied field parallel to c-axis, since the KTP crystal belongs to the rhomboic mm-2 system. For the crystal length L and the wavelength λ, the phase shift (phase retardation) of the f and s axis components of the transmitted wave is given by the Appendix equation

$$\delta = \frac{2\pi}{\lambda} (n_{w,f} - n_{w,s'})L$$

where $n_{w,f}$ and $n_{w,s'}$ are the refractive indices for the f and s axis components of the fundamental wave in the presence of the electric field ($n_{w,f} < n_{w,s'}$). From this relation, we can derive the polarization characteristic of the transmitted fundamental wave.

There remains a second question concerning the phase matching condition in the presence of the electric field. We derive the second-harmonic phase shift from the phase matching condition as given in the Appendix by

$$\delta_s = \frac{\pi}{\lambda} \left( 2n_{2w,f} - (n_{w,f} + n_{w,s'}) \right) L$$

where $n_{2w,f}$ is the refractive index of the f axis component for the SH wave.

Figure 2 shows the calculated results of the applied voltage dependence of the fundamental phase shift $\delta_f$ and the second-harmonic phase shift $\delta_s$ in the KTP crystal for type II phase matching with $\phi = 23.4^\circ$ and $\theta = 90^\circ$. In the calculation, we used the values shown across the bottom of the page, from [9].

We assumed that the KTP crystal length is $L = 5$ mm and the thickness along the c-axis is $t = 1$ mm. The electric field applied parallel to the c-axis is $E_0 = V_0 t$, where $V_0$ is the applied voltage to the KTP crystal. From the results of Fig. 2 it is shown that $\pi/2$ phase shift of the fundamental wave is obtained by applying $V_{e/2} = 738$ V and the transmitted-wave polarization is changed from linear to circular. The phase shift of the SH wavelength by this voltage is within the SHG phase matching acceptance condition; $\delta_s < \pi$. This indicates that it is possible to control the polarization of the fundamental wave for the electrooptic Q-switching while maintaining the second-harmonic phase matching condition.

III. EXPERIMENT

A. Characteristics of CW Operation of a Short-Cavity Nd:YVO₄ Laser

Nd:YVO₄ crystals belong to the zircon (ZrSiO₄) tetragonal space group and the Nd³⁺ ion in this host shows generally similar absorption and emission spectra to the Nd⁴⁺ ion in YAG [14]. The absorption spectrum at 809 nm exhibits somewhat broader width of ~2.8 nm and a large absorption coefficient of 31.1 cm⁻¹ for 1.1-at.-% Nd, making the material more suitable for diode laser pumping than Nd:YAG as a miniature laser material at 1.064 μm and 1.35 μm [4], [15], [16].

Figure 3 shows the experimental setup of the diode laser pumped short-cavity Nd:YVO₄ laser. The laser chip was made from a rod of YVO₄ crystal with 1.1-at.% Nd³⁺ doping (NEC) and cut into pieces of 3 mm x 3 mm and polished to a thickness of 500 μm. The surface of the crystal which faces the diode laser had a transmission of 95.0% at the pump wavelength and reflectivity of 99.9% at 1.064 μm and 532 nm as a resonator mirror. The opposite surface was antireflection-coated, with a transmission of 99.9% at 1.064 μm and 532 nm. The short-cavity laser was longitudinally pumped by a diode laser (Sony SLD-304V) with 760-mW maximum output power at 809 nm, and the diode laser beam was focused into a spot size varying from 100 to 400 μm in diameter.

First, in order to evaluate the basic performance of this laser, the 1.064-μm output was measured, without the KTP crystal in the cavity. The input–output curve for CW operation is shown in Fig. 4. The output mirror had a reflectivity of 95.6% at 1.064 μm, a radius of curvature of 100 mm, and a cavity length of 50 mm. The threshold was measured to be 157 mW, and the slope efficiency was $\eta_s = 51.5%$. The maximum output power of the short-cavity laser was 308 mW, and the optical efficiency was $\eta_o = 40.5%$ in multimode oscillation at 760-mW pump power. The output beam was circularly symmetric with a divergence angle of ~4 mrad.
B. Laser Characteristics

The intracavity frequency doubling experiments were carried out using the KTP (crystal-A) of 5-mm length (CASTECH). The crystal was cut for type II phase matching and antireflection-coated for the fundamental and second-harmonic wavelengths. The output mirror had a reflectivity of 99.9% at 1.064 mm, a transmission of 99.0% at 532 nm, and a radius of curvature of 50 mm. The cavity length was 21 mm for the hemispherical resonator.

The CW SH output power of this laser is also plotted as a function of pumping power in Fig. 4. The lasing threshold was increased to 490 mW. The maximum SH output power of the short-cavity laser was 69.5 mW, and the optical efficiency was \( \eta_0 = 9.1\% \) in multiaxial mode oscillation was 760-mW pump power. The output beam was circularly symmetric, with a divergence of \( \sim 5.2 \) mrad.

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B. Laser Characteristics of Q-switched Operation

YVO\(_4\) is a strongly birefringent uniaxial crystal, and the Nd transitions are strongly polarized. The emission cross section of the \( \pi \) polarization (parallel to the \( c \)-axis) is about 4.2 times larger than that of the \( \sigma \) polarization (perpendicular to the \( c \)-axis). The lasing transitions occur for the \( \pi \) polarization, which means that electrooptic Q-switching can be accomplished without an intracavity polarizer [17].

Next, the Q-switched oscillation of the intracavity frequency-doubled Nd:YVO\(_4\) laser shown in Fig. 3, was investigated. The KTP (crystal-B) that was used for Q-switching and frequency doubling was cut into \( 1 \times 3 \times 5 \) mm\(^3\) and the thickness along the \( c \)-axis was \( t = 1 \) mm, with the electrodes deposited on the two faces normal to the \( c \)-axis. The crystal was also cut for type II SH phase matching.

Before the Q-switching oscillation we examined the maximum SH output power to be 25 mW in CW operation. The decrease in the power is originated because the loss of the antireflection coating on the KTP (crystal-B) was larger than the previous crystal-A.

In the Q-switching oscillation incident angle of the KTP crystal was adjusted to work as a \( \lambda/4 \) plate, without applying the voltage. In this condition the laser is kept under the oscillation threshold. When the high-voltage pulse of \( V_{e/2} \) is applied to the KTP crystal, the loss of the fundamental wave decreases since the crystal works as a \( \lambda/2 \) plate. As a result, the Q-switched and the frequency-doubled laser operation is achieved. However, because KTP has ionic conductivity, high voltage was applied in a short period of a few microseconds.

Optimum Q-switching operation of the laser was obtained when the applied voltage was \( \sim 750 \) V. This voltage corresponded to the half retardation voltage \( V_{e/2} \), which is in good agreement with theoretical results of \( V_{e/2} = 738 \) V shown in Fig. 2.

The output pulse shape is shown in Fig. 5. The FWHM width of the output pulse was \( \sim 18 \) ns with 760-mW pump power, and no after pulsing was observed. The peak SH output power and pulse width versus pump power of the Q-switched operation of the intracavity frequency doubled laser are shown in Fig. 6. The pulse width decreases from 80 ns to 18 ns by increasing the pump power from 170 to 760 mW. The lasing threshold was measured to be 170 mW and the maximum output peak power was 15.4 W at 760-mW pump power. The pulse repetition rate was 100 Hz, and the average output power was 27.7 \( \mu \)W. The repetition rate was limited by the current capacity of the electric circuit. The peak second-harmonic power was increased in the Q-switched operation by a factor of 616 from the CW power level. In addition to the loss of the crystal coating, this peak power was also limited by the slow rise time of \( \sim 100 \) ns of the applied high voltage.

IV. Conclusion

In this paper we have presented an analysis of electrooptic characteristics and SHG phase matching conditions of the type II KTP. From these results it was predicted that the Q-switching operation is possible by controlling the polarization of the fundamental wave for the crystal where the SHG phase-matching condition.

We have developed an intracavity frequency-doubled Nd:YVO\(_4\) laser pumped by a diode laser using the type II KTP. By applying the high-voltage pulse to the KTP crystal, which was used as a frequency-doubled crystal, electrooptic Q-switching operation was demonstrated. The lasing transitions are polarized since Nd:YVO\(_4\) is a strongly birefringent uniaxial
crystal. From this property electrooptic Q-switching was accomplished without an intracavity polarizer. Maximum green peak output power of 15.4 W was obtained with an 18-nsec pulse width at repetition rate of 100 Hz. Although this output power was enhanced 616 times for the CW level, it was limited by the KTP reflection loss and the rise time of Q-switch driver. Peak power of a few kilowatts at a few kilohertz repetition rate should be realized by improving these factors.

Diode laser pumped Nd:YVO4 lasers using this novel Q-switch and SHG device, should be desirable, compact, and reliable green sources for practical applications in the future in remote sensing (laser radar), underwater communication, and optical storage.

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APPENDIX

Figure A1 shows a typical index ellipsoid of a biaxial crystal, where the crystal axes are $a$, $b$, and $c$, and the principal refractive indices are $n_{\omega, a}$, $n_{\omega, b}$, and $n_{\omega, c}$, respectively. An equation of the index ellipsoid in the presence of the electric field is given by

$$a_{11}X_1^2 + a_{22}X_2^2 + a_{33}X_3^2 + 2a_{23}X_2X_3 + 2a_{31}X_3X_1 + 2a_{12}X_1X_2 = 1$$

(A1)

where $X_i (i = 1, 2, 3)$ is parallel to the principal dielectric axis of the crystal (we use the conversion $1 = a, 2 = b, 3 = c$), $a_{ij}$ is relative optical dielectric impermeability [13]. Since KTP crystal belongs to the rhombic mm-2 system, the optical dielectric impermeability $a_{ij}$ in the presence of the electric field is

$$a_{11} = \frac{1}{n_{\omega, a}^2} + r_{13}E_3$$

(A2a)

$$a_{22} = \frac{1}{n_{\omega, b}^2} + r_{23}E_3$$

(A2b)

$$a_{33} = \frac{1}{n_{\omega, c}^2} + r_{33}E_3$$

(A2c)

$$a_{23} = r_{43}E_3 = 0$$

(A2d)

$$a_{31} = r_{53}E_3 = 0$$

(A2e)

$$a_{12} = r_{63}E_3 = 0$$

(A2f)

where $r_{ij}$ is the electrooptic coefficient, and $E_3$ is the electric field parallel to the c-axis [13]. Then we obtain the equation of index ellipsoid for KTP in the presence of the electric field as

$$\left(\frac{1}{n_{\omega, a}^2} + r_{13}E_3\right)X_1^2 + \left(\frac{1}{n_{\omega, b}^2} + r_{23}E_3\right)X_2^2 + \left(\frac{1}{n_{\omega, c}^2} + r_{33}E_3\right)X_3^2 = 1.$$  

(A3)

We thus find that the equation contains no mixed terms: $X_2X_3, X_3X_1,$ and $X_1X_2$. This means that the major axes of the ellipsoid, with the electric field, are parallel to the $X_1, X_2,$ and $X_3$ crystal axes. The lengths of the major axes of the ellipsoid depend on the applied field. From (A3), the new refractive indices are given by

$$n_{\omega, a'} = n_{\omega, a} - \frac{1}{2}n_{\omega, a}r_{13}E_3$$

(A4a)

$$n_{\omega, b'} = n_{\omega, b} - \frac{1}{2}n_{\omega, b}r_{23}E_3$$

(A4b)

$$n_{\omega, c'} = n_{\omega, c} - \frac{1}{2}n_{\omega, c}r_{33}E_3$$

(A4c)

For a fundamental wave propagating in the biaxial crystal at angle $\theta$ and $\phi$ with respect to the principal axes $c$ and $a$, respectively, the refractive index $n_{\omega, i'} (i = f, s)$ is given by Fresnel's equation

$$\sin^2 \theta \cos^2 \phi + \sin^2 \theta \sin^2 \phi = \frac{n_{\omega, b'}^2 - n_{\omega, a'}^2}{n_{\omega, f'}^2 - n_{\omega, b'}^2} + \frac{n_{\omega, f'}^2 - n_{\omega, a'}^2}{n_{\omega, s'}^2 - n_{\omega, c'}^2}$$

(A5)

Equation (A5) can be solved by a quadratic equation for $n_{\omega, a'}$. Thus the refractive index $n_{\omega, i'}$ has the following two values for a given value of angle $\theta$ and $\phi$.

$$n_{\omega, i'} = \sqrt{\frac{2}{B_\omega \pm \sqrt{B_\omega^2 - 4C_\omega}}}$$

(A6)

where

$$B_\omega = (n_{\omega, b'}^2 + n_{\omega, c'}^2)X^2 + (n_{\omega, a'}^2 + n_{\omega, c'}^2)Y^2 + (n_{\omega, b'}^2 + n_{\omega, c'}^2)Z^2$$

$$C_\omega = n_{\omega, a'}^2 n_{\omega, f'}^2 X^2 + n_{\omega, a'}^2 n_{\omega, s'}^2 Y^2 + n_{\omega, c'}^2 n_{\omega, s'}^2 Z^2$$

$$X = \sin \theta \cos \phi$$

$$Y = \sin \theta \sin \phi$$

$$Z = \cos \theta.$$  

As $i = f, s$, the symbols under the square root sign take on plus or minus values, respectively ($n_f < n_s$).

We then consider the case where the crystal is used simultaneously for frequency doubling in type II phase matching. For the crystal length $L$ and the fundamental wavelength $\lambda$, the phase difference between the $f$ and $s$ axis components in the crystal is given by

$$\delta = \frac{2\pi}{\lambda} (n_{\omega, f'} - n_{\omega, s'})L$$

(A7)

where $n_{\omega, f'}$ and $n_{\omega, s'}$ are given by (A6) with type II phase matching angles. From this equation we obtain the polarization characteristics of the transmitted fundamental wave.
Another question is the phase-matching condition in the presence of the electric field. The type II phase-matching condition is given by

$$\frac{1}{2}(n_{2w,f} + n_{2w, s}) = n_{2w,f}$$  \hspace{1cm} (A8)$$

where $n_{2w,f}$ is the refractive index for the second-harmonic frequency. Similarly with (A6), the refractive indices in the presence of an electric field $E_3$ are given by

$$n_{2w,f} = \sqrt{\frac{2}{B_{2w} \pm \sqrt{B_{2w}^2 - 4C_{2w}}}}$$  \hspace{1cm} (A9)$$

where

$$B_{2w} = (n_{2w, r}^2 + n_{2w, c}^2)X^2 + (n_{2w, r}^2 + n_{2w, c}^2)Y^2$$
$$C_{2w} = n_{2w, r}^2n_{2w, c}X^2 + n_{2w, r}^2n_{2w, c}Y^2$$
$$+ n_{2w, r}n_{2w, c}^2Z^2.$$

By applying the electric field, the second-harmonic phase is shifted from the phase-matching condition as given by

$$\delta_s = \frac{\Delta kL}{2} = \frac{\pi}{\lambda} \left\{ 2n_{2w,f} - (n_{2w,f} + n_{2w,s}) \right\} L.$$  \hspace{1cm} (A10)$$

From (A7) and (A10), we can compare the fundamental phase shift with the second-harmonic phase shift in the KTP crystal for type II phase matching.

REFERENCES


Takumi Kobayashi was born in Fukui, Japan, in 1960. He received the B.E. and M.E. degrees in electrical engineering from Fukui University, Japan, in 1983 and 1985, respectively. He joined LSI Research and Development Laboratory of Mitsubishi Electric Co. in the same year, where he was involved in the research of a 32-bit microprocessor and cash memory. He is currently a research associate of Electrical and Electronics Engineering, Fukui University, and is involved in the research of diode-pumped solid-state lasers, nonlinear frequency conversion, and their applications.

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