$KNbO_3$ temperature-tuned blue laser

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Abstract. We present the properties of a tunable blue laser obtained from a laser-diode (LD)-pumped Cr:LiSAF solid state laser doubled by $KNbO_3$ (KN) crystal. We show the calculations for KN crystal phase matching in the *xy, yz*, and *xz* planes, the effective nonlinear coefficient and the noncritical phase-matching (NCPM) temperature tuning. We analyze the practicality of a temperature-tuned and LD-pumped blue laser that uses KN and investigate the relation between the output wavelength of a KN-doubling Cr:LiSAF laser and the temperature variation. The temperature-tuned blue laser with continuous output from 423.5 to 446 nm is obtained with a temperature range of −5 to 100°C. [S0091-3286(99)00111-7]

Subject terms: tunable blue laser; $KNbO_3$ crystal; frequency conversion; noncritical phase matching; birefringence.

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1 Introduction

In recent years, the appearance of new types of laser crystals pumped by laser diodes (LDs) such as $Nd:YVO_4$, Cr:LiSAF, Cr:LiCAF, and $Nd:BeAlO_4$ has stimulated the further development of LD-pumped solid state lasers[1] (DPSSLs). Especially, the products of a LD-pumped $Nd:YVO_4$ solid state cw green laser with 10-W output have already been commercialized.[2] Currently, the research on the solid state small-sized blue laser devices are performed mainly in wave-guided and LD devices. The wave-guided laser has realized milliwatt output in the 425-nm wavelength using $KTiOPO_4$ and $LiNbO_3$/KTP wave-guided direct doubling.[3,4] Such laser devices have the advantage of high conversion efficiency, but the light beam of the second harmonic generation (SHG) output is of low quality. Moreover, since the technique of manufacturing wave-guided devices is complicated, it may be difficult to obtain practical devices.

A blue laser emitted directly by an LD is the most desirable. The 3M company has reported blue laser devices based on semiconductors of the II–VI subgroup, and a blue pulse laser emitting 490-nm-wavelength light was obtained[5] at the low temperature of 77 K. In 1997, the normal temperature lifetime of a 401-nm blue LD by Nichia Chemical Corporation reached[6] 10,000 h. The lifetime reached this requirement, but there is still a long way to go to achieve practical application because of the low quality of light beams. The blue laser made by Shimadzu Company using LBO doubling for 946-nm emission of Nd:YAG achieved 473-nm blue output, and the company has developed a 10-mW commercial laser.[7] The LD pumped Cr:LiSAF laser was cooperatively developed by Melles Griot. The LBO-doubling blue laser with 10-mW output at a 430-nm wavelength made by Hitachi was also commercialized.[8] These lasers, however, have only single wavelength outputs, which limit the actual applications for industry and the spectrum analysis in the blue wavelength range. Thus if tunable output in the blue region is obtained, its significance will increase in many fields.

Tunable blue lasers using the wave-guided and LD devices alone cannot be realized owing to the limits in their materials and structures. Therefore, LD-pumped solid state lasers using frequency-doubling elements became important for tunable blue laser oscillation. In this case, the intracavity frequency doubling method with nonlinear crystals is generally used. Among nonlinear crystals such as KDP, KD*P, $LiIO_3$, KTP, LBO, BBO, KN($KNbO_3$), and $LiNbO_3$,[9] KTP, which has larger nonlinear coefficients and nondeliquescence, can well serve as an SHG device for 532-nm green lasers. However, it cannot be applied to the generation of blue lasers since the lowest phase-matching wavelength of KTP is 991 nm.[10] Crystals that can serve this purpose are LBO and KN. LBO nonlinear coefficients are small and the doubling conversion efficiency for the low-power laser is low. On the other hand, KN crystal has larger nonlinear optical coefficients and advantageous noncritical phase-matching (NCPM) properties.[11] KN crystal, therefore, may be suitable for the blue lasers.

Since the tunable blue lasers have not yet succeeded in LD-pumped solid state lasers, we performed tunable experiments using the KN crystal in a variable temperature environment. From the experiments, blue tunable laser output could be obtained using a temperature-tuned LD-pumped Cr:LiSAF laser with KN crystal for the intracavity frequency-doubling device.

2 Phase-Matching and Temperature-Tuned Properties of KN Crystal

KN is a negative biaxial, orthorhombic symmetric, and millimeter squared point group crystal. The stable temperature range of an orthorhombic is from −50 to 220°C, and the transparency range is 400 to 4500 nm. The relation between principal axes and crystallographic axes is as $x \Leftrightarrow c$, $y \Leftrightarrow a$, and $z \Leftrightarrow b$, and $n_b > n_a > n_c$. The Sellmeier equations for KN refractive index are as follows[12]:

$$n_x^2 = 4.4208 + 0.10044/(\lambda^2 - 0.054084) - 0.019592\lambda^2, \quad (1)$$

$$n_y^2 = 4.8355 + 0.12839/(\lambda^2 - 0.056342) - 0.025379\lambda^2, \quad (2)$$

$$n_z^2 = 4.9873 + 0.15149/(\lambda^2 - 0.064143) - 0.028775\lambda^2. \quad (3)$$

The nonlinear polarization coefficients at 1064 nm are $d_{31} = -15.8$ pm/V and $d_{32} = -18.3$ pm/V. According to the nonlinear optical principle and the phase-matching theory of biaxial crystal,[13] for type I phase matching of KN doubling, the phase-matching condition is

$$n'_{\omega} = n''_{2\omega}. \quad (4)$$

Phase-matching angles can be calculated with the following equations[13]:

$$A_{2\omega} - A_{\omega} = (A_{2\omega}^2 - 4B_{2\omega})^{1/2} + (A_{\omega}^2 - 4B_{\omega})^{1/2}, \quad (5)$$

and

$$A = -\sin^2\theta\cos^2\varphi(n_y^{-2} + n_z^{-2}) - \sin^2\theta\sin^2\varphi(n_x^{-2} + n_z^{-2}) - \cos^2\theta(n_x^{-2} + n_y^{-2}). \quad (6)$$

$$B = \sin^2\theta\cos^2\varphi n_y^{-2} n_z^{-2} + \sin^2\theta\sin^2\varphi n_x^{-2} n_z^{-2} + \cos^2\theta n_x^{-2} n_y^{-2}. \quad (7)$$

The effective nonlinear coefficient d_{eff} of KN crystal is the function of its second-order nonlinear polarization coefficient and the phase-matching angle. The relation between them is given by

$$P^{(2)}(\omega_3) = \epsilon_0 d_{\text{eff}}^{(2)} E(\omega_1) E(\omega_2), \quad (8)$$

where $P^{(2)}(\omega_3)$ is the nonlinear polarization intensity amplitude, and $E(\omega_1)$ and $E(\omega_2)$ are the base frequency electric field intensity amplitudes. The relation between the effective nonlinear coefficient and the second-order nonlinear polarizability is given by

$$d_{\text{eff}} = a_i d_{ijk} a_j a_k. \quad (9)$$

In Eq. (9), a_i, a_j, and a_k are, respectively, the unit vectors of $P(\omega_3)$, $E(\omega_1)$ and $E(\omega_2)$. The value of each vector is dependent on the phase-matching angles θ and φ. Effective nonlinear coefficients for KN crystal are $d_{\text{eff}} = d_{32}\sin\varphi$ in the *xy* plane, $d_{\text{eff}} = d_{32}\sin\theta + d_{31}\cos\theta$ in *xy* plane, and $d_{\text{eff}} = d_{31}\cos\theta$ in *xz* plane. KN crystal has a larger nonlinear polarization coefficient and thus the nonlinear optical coefficient is larger. From the preceding equations, we calculated the phase-matching angle and the effective nonlinear coefficient of KN crystal.

Figure 1 shows the phase-matching wavelength range of KN crystal in the *xy* plane from 857 to 4500 nm. In Fig. 1, phase matching can realized in the wavelength range from 857 mn, and the angle as well as the effective nonlinear coefficient changes with the wavelength. From $d_{\text{eff}} = d_{32}\sin\varphi$ in the *xy* plane, $d_{\text{eff}} = 4.429$ is obtained and is the lowest value at the minimum phase-matching angle $\varphi = 15.7$ deg at the wavelength $\lambda = 2090$ nm. Since the shortest matching wavelength is 857 nm, the shortest wavelength obtained from frequency conversion using KN crystal is 428.5 nm. In general, the output power of the LD-pumped Cr:LiSAF solid state laser is low, and thus intracavity frequency doubling is required to obtain a higher conversion efficiency.

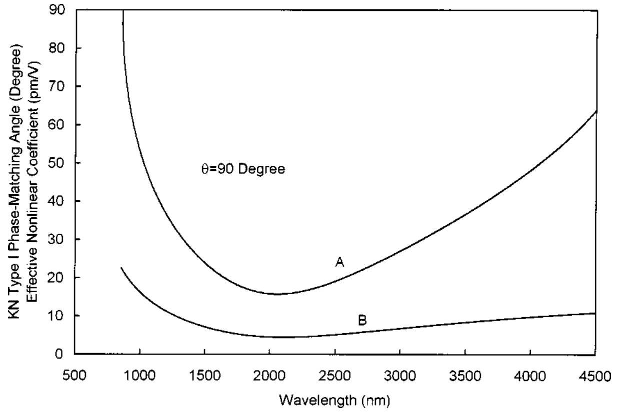

Fig. 1 Phase-matching angle (curve A) and effective nonlinear coefficient d_{eff} (curve B) of KN crystal in the *xy* plane.

Figure 2 indicates that the phase matching of KN crystal cannot be realized in the wide range of wavelength from 983 to 4422 nm in the *yz* plane. KN crystal has two phase-matching wavelength regions in this plane: 857 to 983 nm in the short-wavelength range and 4422 to 4500 nm in the long-wavelength range. The phase matching can be realized only within these two narrow ranges. This property cannot be observed in other nonlinear optical crystals. The phase-matching angle varies mainly with the wavelength, and consequently angle matching and angle tuning by means of KN is not performed in the *yz* plane.

Figure 3 shows that the KN crystal phase-matching wavelength range in the *xz* plane is 983 to 4422 nm. The values of the figure reveal that although 1064-nm Nd laser phase matching can be realized in the *xy* and *xz* planes, the effective nonlinear coefficient of the matching point of $\theta = 18.7$ deg and $\varphi = 0$ deg in the *xz* plane is greater than that of $\theta = 90$ deg and $\varphi = 46.3$ deg in the *xy* plane. The phase-matching point in the *xz* plane is generally used for the doubling of a 1064-nm laser. Unfortunately, the shortest wavelength of angle matching in the *xz* plane is 983 nm, which cannot generate the blue laser output. Under normal temperature, KN crystal can realize both 90-deg and 0-deg NCPM of wavelengths 857 and 983 nm, respectively. This is quite rare for nonlinear optical crystals. Because of several effective properties of NCPM, the large acceptance angle and zero walk-off angle can increase the conversion efficiency. In addition, a high-quality doubling laser output can be obtained. The NCPM wavelength of KN crystal is near 846 nm, which corresponds to the peak point of the Cr:LiSAF emitted spectrum.[14] NCPM, however, cannot be used for angle tuning. To utilize the NCPM property of KN

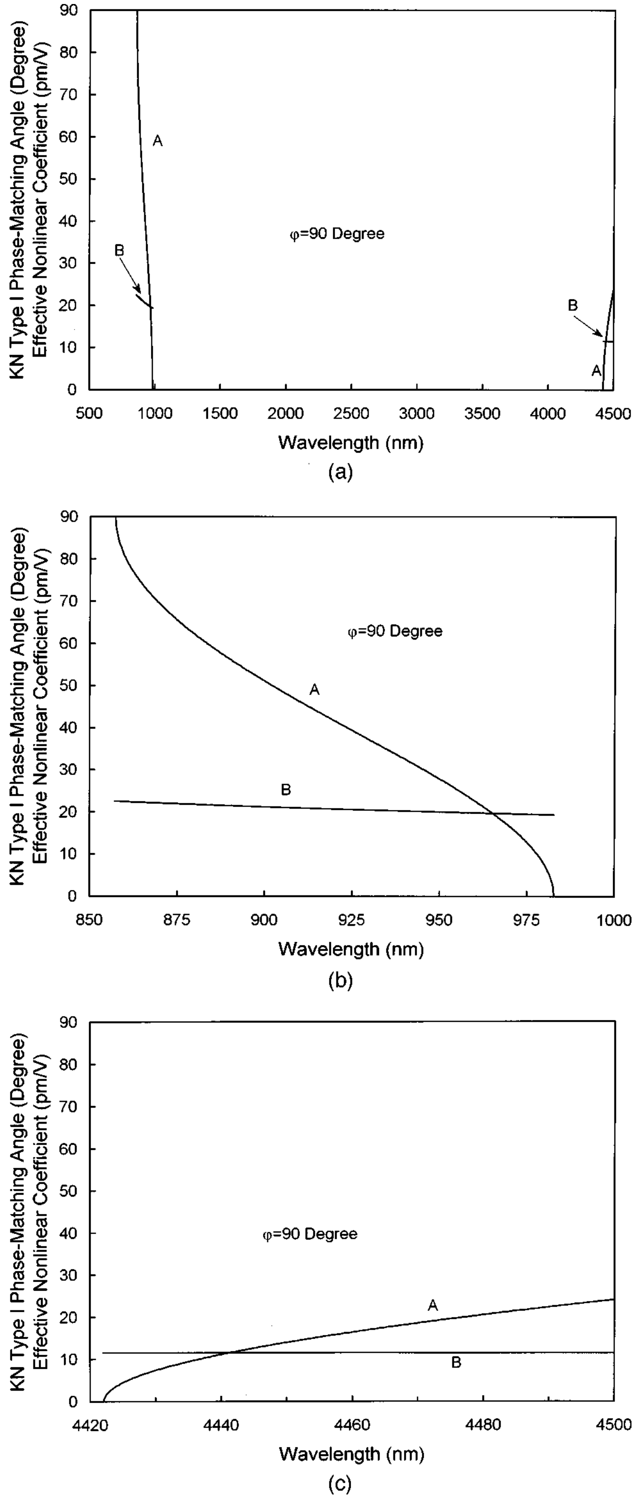

Fig. 2 Phase-matching angle (curves A) and effective nonlinear coefficient $d_{\rm eff}$ (curves B) of KN crystal in the *yz* plane for wavelength ranges (a) from 500 to 4500 nm, (b) from 850 to 1000 nm, and (c) from 4420 to 4500 nm.

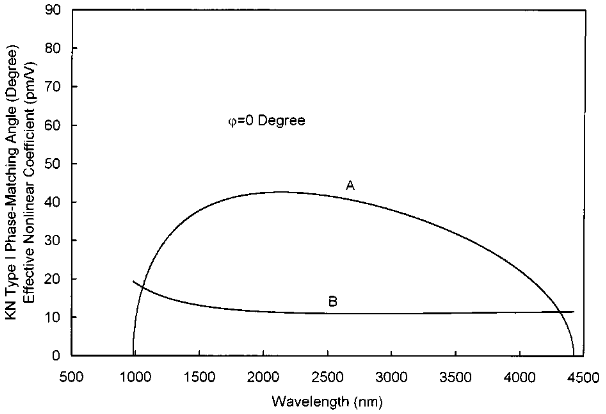

Fig. 3 Phase-matching angle (curve A) and effective nonlinear coefficient $d_{\rm eff}$ (curve B) of KN crystal in the *xz* plane.

and at the same time realize the broad tunable output of a blue laser, we carried out the method by changing the crystal temperature. The refractive index of the nonlinear crystal can be varied by varying the crystal temperature, which changes the crystal phase-matching angle and the NCPM wavelength. The KN crystal refractive index is also changed with temperature[15] and is expressed as

$$n(T,\lambda)=C_0(\lambda)+C_1(\lambda)T+C_2(\lambda)T^2. \tag{10}$$

The relation between the NCPM wavelength of KN crystal and the crystal temperature can be conducted from Eq. (10) as[16]

$$\lambda_{\rm NCPM}=a_0+a_1t+a_2t^2, \tag{11}$$

where $a_0=850.4\,\text{nm}$, $a_1=0.294\,\text{nm/°C}$, and $a_2=1.234\times10^{-3}\,\text{nm/°C}$ for NCPM. From Eq. (11), the 90-deg NCPM temperature-tuned curve of KN crystal can be calculated (see Fig. 4).

Figure 4 illustrates the NCPM temperature tuning range of KN crystal from −40 to 210°C. Since KN crystals have phase changing points at −50 and 220°C, the actual tunable range is limited within −40 to 114°C. Although the Cr:LiSAF crystal emitting intensity is greater in the wavelength range from 789 to 1050 nm, the available range width for LD pumped Cr:LiSAF laser is[17] only from 840 to 900 nm. Thus the NCPM temperature tuning range shows

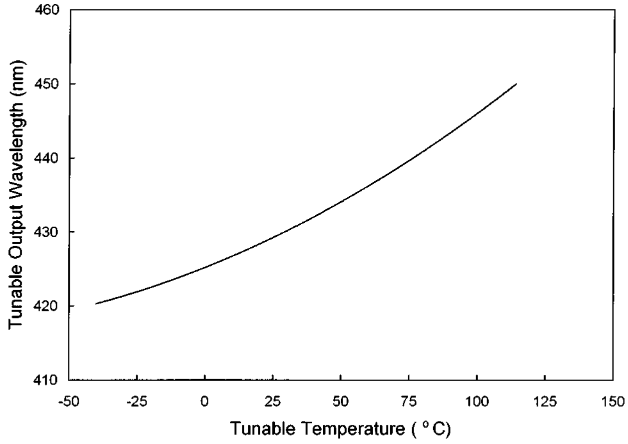

Fig. 4 Temperature dependence of the wavelength for type I NCPM in KN crystal obtained by calculation.

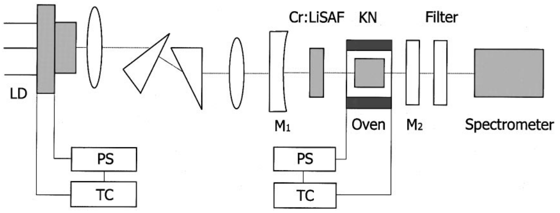

Fig. 5 Schematic of the KN-doubling Cr:LiSAF laser to obtain tunable blue laser output: PS, power supply, and TC, temperature controller.

that it is adequate for doubling of the LD-pumped Cr:LiSAF laser to achieve the blue laser tunable output.

3 Experiment Results

The experimental schematic arrangement of the temperature-tuned blue laser using LD-pumped Cr:LiSAF laser doubling is shown in Fig. 5. The size of Cr:LiSAF crystal is $3\times3\times2$ mm^3 and a cut, and doped concentration is 2.2 wt %. The planoconcave cavity is added in the laser system. The reflectivity of the input coupling mirror M_1 is $R\geqslant 99.8\%$ at 860 nm, the transparence $T>90\%$ at 670 nm, and radius of curvature $r=100$ mm. The reflectivity of output mirror M_2 is $R\geqslant 99.8\%$ at 860 nm and the transparence is $T\geqslant 95\%$ at 430 nm. The high reflective bandwidth of the mirror is more than 100 nm. The LD used is model AOC-670-HHL (AOC Company) with an emitting wavelength of 679 nm and a maximum output power of 600 mW. The power supply of the LD is made by the CNI Company and the output current is 2 A. The temperature controller is model FP21 (Shimadzu Company) and the control precision is 0.1°C. The scanning spectrometer is WDM1S (Tongzhou OE Company), with a scanning range from 330 to 1000 nm, and its precision is 0.2 nm. Experiment results are shown in Fig. 6.

The results indicate that in the temperature tuning range from −5 to 100°C, the blue laser output can be continuously tuned from 423.5 to 446 nm. The temperature tuning range is limited by the performance of the temperature control unit. The difference of the measured values from theoretical calculation is <1 nm, within the limit of permissible error. From Fig. 6, the experiment results are obviously below those of theoretical calculations when the temperature is below 25°C. This may be caused by the fluctuation errors in the cooling temperature control unit. In our experiments, the laser threshold was 89 mW and the maximum blue laser output was 5.2 mW at the wavelength of 430 nm with a pump power of 250 mW, so that conversion efficiency is 2.08%. Figure 7 shows the blue laser output pumped by a 679-nm LD. The output power is increased from 0.9 mW at 423.5 nm to 5.2 mW at 430 nm when the temperature of KN crystal is changed from −5 to 30°C. When we increase the temperature of the KN, the output wavelength also increases, but the output power is decreased. The output power has a peak near 430 nm. When the temperature reached 100°C, the output power became 1.2 mW. The fluctuation of the doubling blue output is relatively large and this may arise from the mode competition due to undulation of temperature and pumping light.

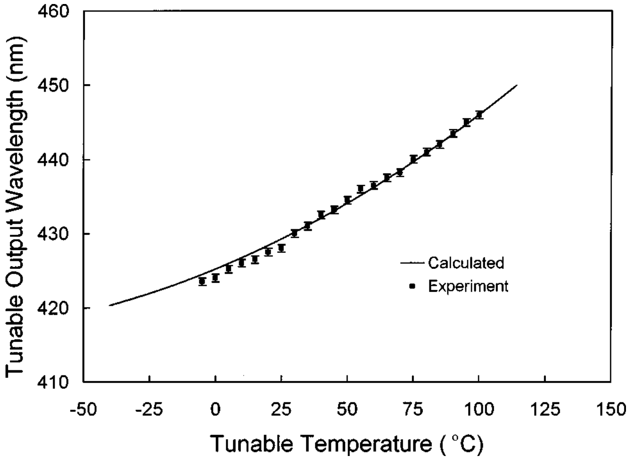

Fig. 6 Temperature-tuned property of blue laser output for a KN-doubling LD-pumped Cr:LiSAF laser.

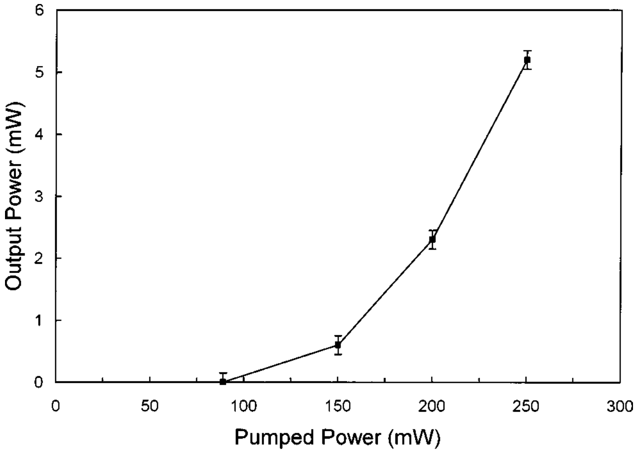

Fig. 7 Output property of a blue laser pumped by a 679-nm LD.

It was found from experiments that insertion of a quarter-wave plate in the laser system can improve the stability of approximately 3% of the output and the maximum linewidth of the output is 3 nm without wavelength selectors. This comparatively wide value may be due mainly to temperature fluctuation, and therefore if the stability of the temperature in the control unit is increased a narrow linewidth will be obtained.

4 Conclusion

To obtain the tunable blue laser output from an LD-pumped Cr:LiSAF laser, we performed theoretical calculations of the KN crystal phase-matching properties. Through the analysis of the LD-pumped Cr:LiSAF laser output, we found that the tunable blue laser output cannot be obtained by means of the angle tuning with KN crystal frequency doubling of the LD-pumped Cr:LiSAF laser. From this result, we used the NCPM property of the KN crystal for laser tuning and the method of changing the KN crystal temperature. When the temperature was changed from −5 to 100°C, a continuous tunable blue laser output from 423.5 to 446 nm was obtained, and the experiment results conform well to the values obtained by the theoretical calculations. In this experiment, the linewidth is approximately 3 nm without wavelength selectors. If the temperature control system is improved and wavelength selector devices are added, the output properties will be further improved.

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