Peculiarities of temperature-dependent Sellmeier equations for periodically poled $KTiOPO_4$ crystal in the near-infrared and visible ranges

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ABSTRACT

Crystals of periodically poled $KTiOPO_4$ (PPKTP) are considered to be promising candidates for the femtosecond OPOs when compared with conventional periodically poled $LiNbO_3$ (PPLN) crystals that suffer from the large photorefractive effect, thermal damage and high coercive field. In order to design the poling period of PPKTP crystal and to predict the desired wavelength tuning range with required spectral characteristics an accurate calculation using the wavelength- and temperature-dependent Sellmeier equations should be carried out. Although the Sellmeier equations for PPKTP have been published and revised several times, there are still some discrepancies between the measured and the theoretical results. It was reported that a temperature shift of approximately 25 °C has to be introduced in that equation in order to match the experimental results in the near-infrared range. In our work this effect is studied in detail in both the near-infrared and visible ranges in order to provide an accurate reference for the design of PPKTP crystals for various nonlinear frequency conversion applications.

Keyword list: Nonlinear optics, periodically poled KTP

1. INTRODUCTION

Optical parametric oscillators (OPOs) are widespread and versatile sources for generating frequency-tunable coherent continuous wave or pulsed radiation in a broad spectral range that spans from the infrared to the ultraviolet [1]. Especially, the ultrafast OPOs have proven to be a powerful tool in, for example, biomedical imaging, communication and gas detection [2-4], benefiting from its wide tunable range, short pulse duration, high peak power at low average power, and high repetition rate. The parametric process that occurs in OPO cavities involves a second-order nonlinear interaction, under which two output fields called signal (ω_s) and idler (ω_i) are generated. The frequencies of the signal field, the pump field, and the idler field satisfy the relation $\omega_s + \omega_i = \omega_p$, where ω_p is the frequency of the pump field. The phase matching is an essential condition for the effective generation of the signal and idler fields. The traditional birefringent phase matching incurs some problems and restrictions to the interactions, such as spatial walk-off and inconvenient phase-matching temperatures and angles, and even cannot be realized in plenty of mediums [5]. Thanks to quasi phase matching (QPM), interactions can be noncritically phase matched in any media. Besides, interactions based on the QPM are more efficient, since large nonlinear coefficients can be conveniently selected.

Periodically poled lithium niobate (PPLN) is the most commonly used medium for near-infrared OPOs. In comparison with other periodically poled mediums, PPLN has a large effective nonlinear coefficient of 17 pm/V when the $e \rightarrow e + e$ interaction is employed [1]. However, PPLN suffers from several drawbacks that limit its usage in many applications. The major problem is the optical damage caused by its large photorefractive effect. Although this problem can be reduced by either heating the medium above 100 °C or doping the medium with MgO [5-6], it increases the complexity of the system and decreases the wavelength tuning range. Another problem of PPLN involves its large coercive field of

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21 kV/mm, which limits the thickness of the medium to around 0.5 mm. Periodically poled $KTiOPO_4$ (PPKTP) is a promising alternative to PPLN for wavelength tuning in the near-infrared region. It also has a large nonlinearity of 9.5 pm/V [7] and, more importantly, PPKTP is resistant to the photorefractive damage when operating even at room temperature. The coercive field of PPKTP is ten times lower than that of PPLN, indicating the possibility of a much larger crystal thickness. Therefore efficient OPOs with high average output power can be realized in PPKTP crystals pumped by a powerful laser system.

Up to the present, almost all of the PPKTP based OPOs were pumped by the Nd:YAG or Nd:YVO_4 lasers operating at 1064 nm, or by their frequency-doubled versions operating at 532 nm [2, 7-9]. These lasers were mainly used in the Q-switched mode and the output pulses usually had the duration of several nanoseconds. Even though they can be operated in the mode-locked mode, the pulses are limited to several picoseconds due to the narrow gain bandwidth of the Nd-doped crystalline materials. One choice of the pump sources for femtosecond OPO is to use a passively mode-locked Ti:sapphire laser. However, the Ti:sapphire laser needs to be pumped by expensive and complicated green-output lasers. Moreover, the lasing efficiency of Ti:sapphire crystal is quite low, limiting its typical output power to around 1 W. An alternative pump source for femtosecond OPO is a new class of femtosecond lasers based on the Yb-doped materials, whose typical emission is centered at 1040 nm. In comparison with Ti:sapphire lasers, the Yb-ion solid state lasers can be pumped by the cheap and efficient laser diodes, indicating the possibility of building compact and cost-effective OPO systems. In addition, the Yb-ion solid state lasers are more efficient than Ti:sapphire lasers. Up to the present, the average output power as high as 76 W has been demonstrated from the Yb:YAG laser [10]. As a result, the PPKTP based OPOs pumped by Yb-ion solid state lasers are promising as efficient and reliable wavelength tunable sources.

Before designing OPOs, a theoretical calculation is necessary to determine the dependence of the wavelength tuning on the parameters of PPKTP crystal such as grating periods, temperature and crystal angles. In our previous work [11], the wavelength tuning as a function of grating periods and temperature was investigated in detail by using a recently published Sellmeier equation [12]. Although the Sellmeier equations for PPKTP have been published and revised several times, there are still some discrepancies between the measured and the theoretical results. It is believed that a temperature shift around 25 °C should be introduced for the theoretical calculation in the near-infrared range [12]. In this work, the temperature shift is studied in detail for the PPKTP based OPO pumped by near-infrared and visible radiation, in order to provide a more accurate theoretical reference for the design of OPOs pumped by ultrafast Yb-ion solid state lasers and their frequency-doubled outputs.

2. THEORETICAL MODEL AND SELLMEIER EQUATIONS

To exploit the largest effective nonlinear coefficient in PPKTP, the pump, signal and idler fields with extraordinary polarizations are used. Based on this consideration, the wavelength of the signal and idler fields should yield the energy conservation and quasi-phasematching condition with the following forms:

$$\frac{1}{\lambda_s}+\frac{1}{\lambda_i}=\frac{1}{\lambda_p} \tag{1}$$

$$\frac{n_e(\lambda_p,T)}{\lambda_p}-\frac{n_e(\lambda_s,T)}{\lambda_s}-\frac{n_e(\lambda_i,T)}{\lambda_i}-\frac{1}{\Lambda(T)}=0 \tag{2}$$

where the λ_s, λ_i and λ_p are the signal, the idler, and the pump wavelengths, respectively. $\Lambda(T)$ is the grating period of the crystal, and is slightly affected by temperature due to thermal expansion of the material. $n_e(\lambda_s,T)$, $n_e(\lambda_i,T)$ and $n_e(\lambda_p,T)$ are the extraordinary refractive indices of the signal, the idler, and the pump fields, respectively. The extraordinary refractive index depends on the wavelength and the temperature.

Up to the present, there are plenty of Sellmeier equations that were presented to describe the extraordinary refractive indices of both bulk and periodically poled KTP crystals [12-15]. Figure 1 shows some of the results. The dotted line is the theoretical curve of the refractive index dispersion in bulk KTP crystals. This curve fitted the experimental data well for bulk KTP crystals but not for the periodically poled KTP crystals. Moreover, it only considered the wavelength dependence of the refractive index while ignoring the temperature dependence. The dashed and solid lines are the improved theoretical calculations involved both the wavelength dependent Sellmeier equations and the thermo-optic dispersion correction for PPKTP. In this work, the most recent and the best fitted Sellmeier equations are selected.

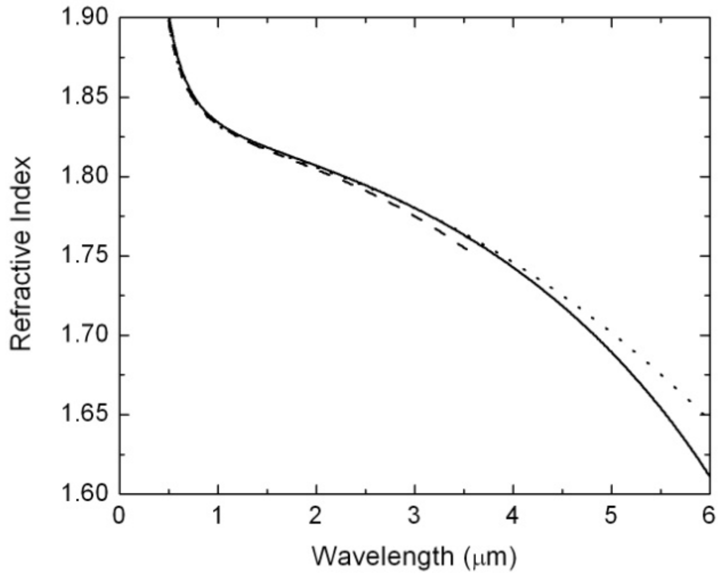

Figure 1. Refractive index dispersion in KTP crystals at 100 °C calculated from different Sellmeier equations. Dotted line is calculated from Sellmeier equation of Vanherzeel *et al* [14]. Dashed line is calculated from Ref. [15]. Solid line is calculated from Ref. [12-13].

The wavelength-dependent Sellmeier equation used in our work has the form of [13]

$$n_e^2 = A + \frac{B}{1 - C/\lambda^2} + \frac{D}{1 - E/\lambda^2} - F\lambda^2 \ , \tag{3}$$

where A=2.12725, B=1.18431, C=5.14852×10^{-2}, D=0.6603, E=100.00507, F=9.68956×10^{-3}. To account for variation of the refractive index with temperature the correction term Δn should be added [12]:

$$\begin{aligned} \Delta n_e &= n_1(T - 25°C) + n_2(T - 25°C)^2 \\ n_1 &= a_0 + \frac{a_1}{\lambda} + \frac{a_2}{\lambda^2} + \frac{a_3}{\lambda^3} \\ n_2 &= b_0 + \frac{b_1}{\lambda} + \frac{b_2}{\lambda^2} + \frac{b_3}{\lambda^3} \end{aligned} \tag{4}$$

where the values of a_m (m=1,2,3) and b_m (m=1,2,3) are listed in Table 1.

Table 1 Coefficients for the temperature-dependent correction term Δn [12]

a_0	a_1	a_2	a_3	b_0	b_1	b_2	b_3
-6.1537×10^{-6}	64.505×10^{-6}	-56.447×10^{-6}	17.169×10^{-6}	-0.96751×10^{-8}	13.192×10^{-8}	-11.78×10^{-8}	3.6292×10^{-8}

3. COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS

Although the Sellmeier equation of KTP crystals has been improved several times, there is still a deviation between the theoretical and the experimental results. Figure 2(a) shows the calculating result by using the formulas listed above directly. It can be seen that the theoretical curve does not fit the experimental data (solid dots) [7] well, especially at high temperature region. Shai Emanueli *et al* mentioned that a temperature shift around 25°C should be considered in the calculation [12]. However, they did not mention whether this temperature shift is positive or negative, and also, the exact value of the temperature shift is required for accurate wavelength tuning prediction.

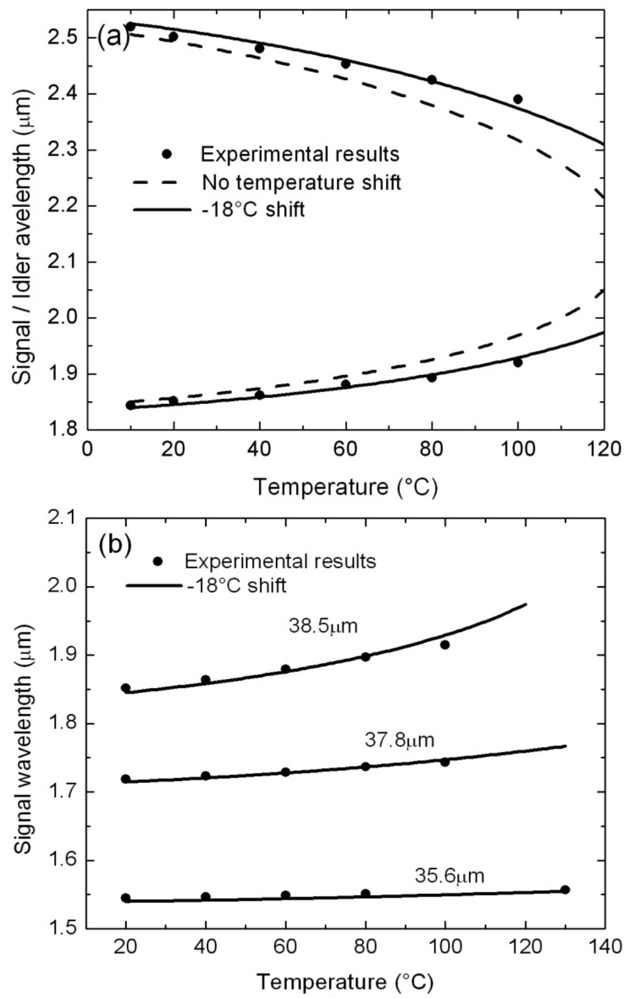

Figure 2. Comparison between the theoretical and experimental results of the OPO wavelength tuning pumped at 1064 nm. The experiment data come from Ref. [7] for (a) and Ref. [8] for (b).

Figure 2(a) also shows the comparison between the experimental data and the theoretical curve calculated with the temperature shift (solid line). The pump wavelength is 1064 nm from a Nd-ion laser and the grating period is 38.5 μm. It can be seen that the theoretical curve fits the experimental data well when a temperature shift of -18 °C is added. The negative sign means the temperature used for the calculation is lower than that for the actual experiment, i.e. if the crystal is set to operate at 50 °C for the experiment, then a temperature of approximately 32 °C should be used to calculate the signal and the idler wavelengths. To verify this temperature shift, the comparison with another set of experimental data available in the literature was made. The results are shown in Figure 2(b). As can be seen, the theoretical curve with -18 °C temperature shift fits the experimental data [8] very well. Moreover, this value does not change with the grating periods.

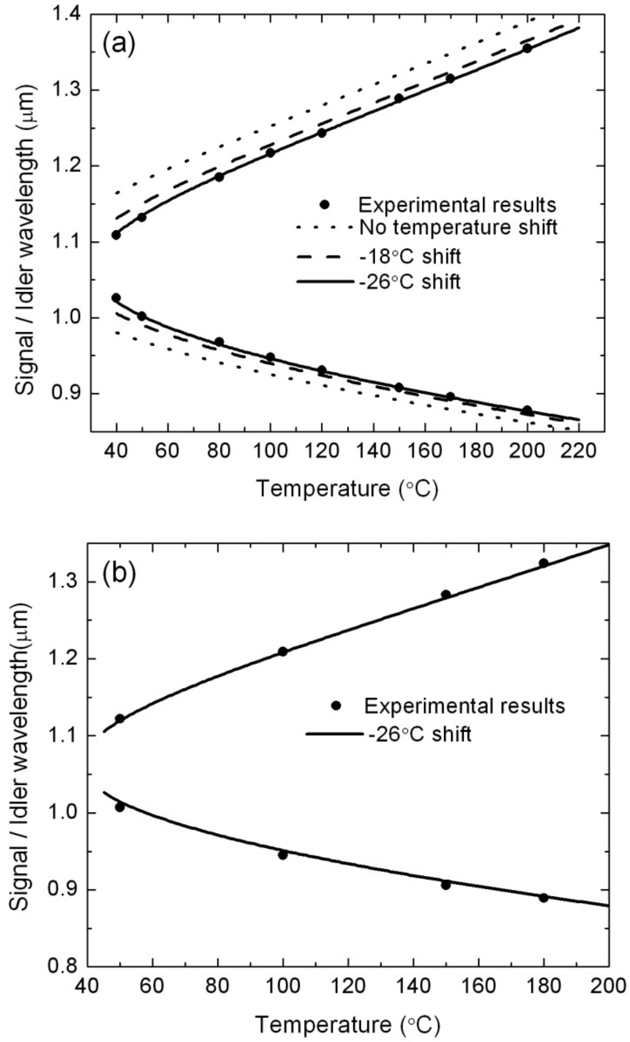

Figure 3. Comparison between the theoretical and experimental results of the OPO wavelength tuning pumped at 532 nm. The experiment data come from Ref. [9] for (a) and Ref. [2] for (b).

The upper limit of the transparent wavelength range of PPKTP crystals is 3.5 μm. From the equation (1), it can be found that this corresponds to the minimum signal wavelength of 1.48 μm when 1064 nm pump is used. If shorter wavelengths are required, the pump wavelength should be shorter than 1064 nm. That is the reason why the frequency doubled output of Nd-ion lasers at 532 nm are often used instead of the fundamental lasing wavelength. A further comparison between the experimental data and theoretical curve is made for 532 nm pump radiation. Figure 3(a) shows the theoretical curves calculated without and with -18 °C temperature shift. It can be seen that the theoretical curve with -18 °C temperature shift still does not fit the data very well, although it works well for 1064 nm radiation. Therefore a new temperature shift of -26 °C was determined as the best value for the needed correction (see Figure 3(a)). Figure 3(b) demonstrates that the -26 °C temperature shift works well and for another set of experimental data points using the 532 nm pump wavelength.

After validating the Sellmeier equations by comparison with published experimental results with Nd-ion pump sources, we calculate the wavelength tuning properties of PPKTP OPO with 1040 nm and 520 nm excitations from the Yb-ion lasers and their frequency doubled versions. Since the lasing wavelengths from the Yb-ion lasers (1030-1045 nm) are quite close to that from the Nd-ion lasers (1064 nm), the values of the temperature shifts that were determined above were used in the calculation. Figure 4 shows the theoretical dependence of the wavelength tuning ranges on the grating periods of a PPKTP OPO pumped at 1040 nm and 520 nm, respectively. The upper branch of each curve is the idler wavelength and the lower one is the signal wavelength. One factor that limits the wavelength tuning range of PPKTP is its transparency over the range of 0.5-3.5 μm. Hence, for a dual oscillating cavity, the wavelength can be tuned from 0.6 μm to 3.5 μm if pumped by 520 nm radiation, and from 1.5 μm to 3.5 μm if pumped by 1040 nm radiation. The degeneracy point for 520 nm excitation occurs at 8.35 μm of grating period and for 1040 nm excitation at 38.24 μm of grating period.

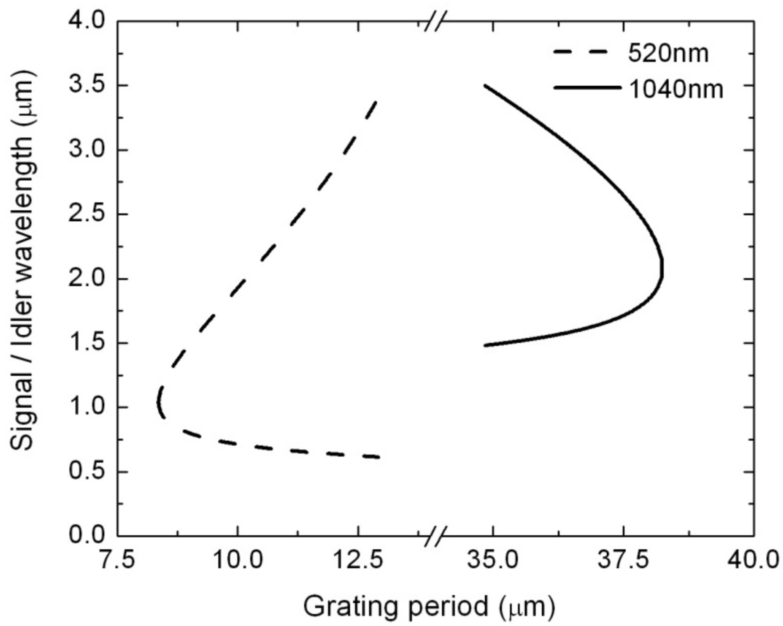

Figure 4. Output wavelength tuning as a function of grating period of PPKTP crystal pumped at 1040 nm and 520 nm.

Fine and continuous wavelength tuning can be realized by tuning the temperature of the crystal as shown in Figure 5. By choosing appropriate grating periods for PPKTP such that their wavelength tuning ranges can overlap with each other, the wavelength can be tuned continuously by varying the temperature and the gratings. Figure 5(a) demonstrates the wavelength tuning of the signal field in the range of 1.48-1.8 μm versus the crystal temperature with the pump field centered at 1064 nm. Figure 5(b) corresponds to the wavelength tuning of the signal field in the range of 1.04-1.65 μm versus the crystal temperature with the pump field centered at 520 nm. The slope of the tuning curve is approximately 1.15 nm/degree and is a little bit higher at smaller grating periods for 520 nm excitation. In contrast, for 1040 nm pump the slope is around 0.22 nm/degree and increases a little at larger grating periods.

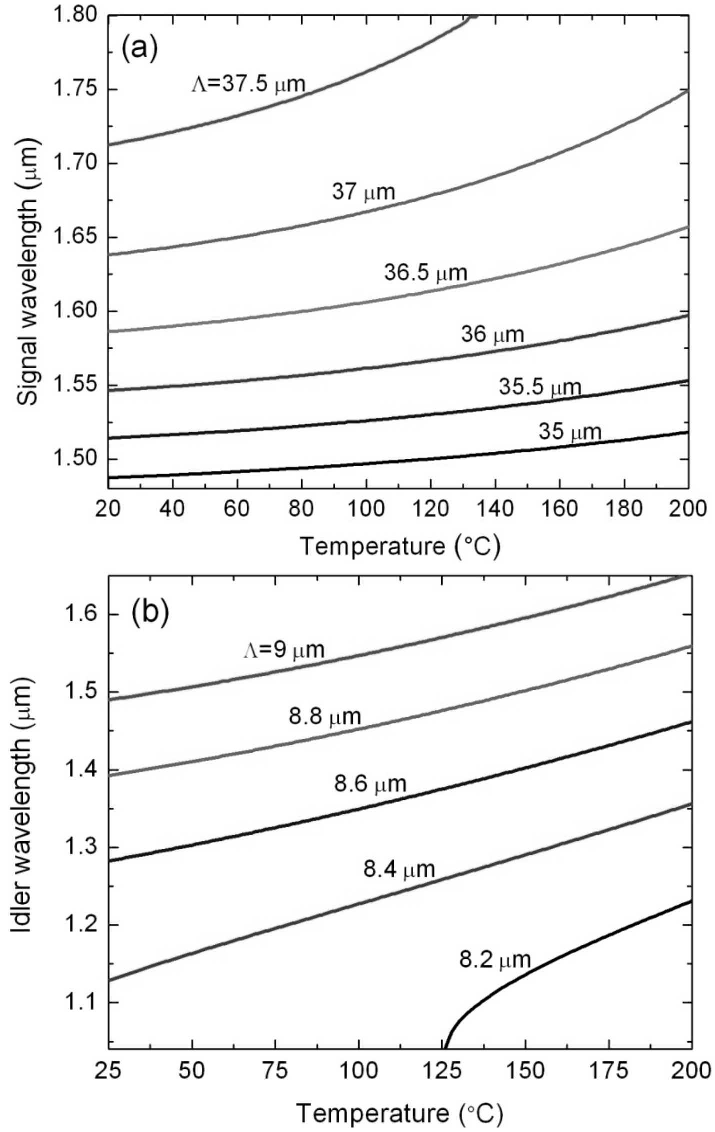

Figure 5. Wavelength tuning as a function of crystal temperature at different grating periods in the range of 1.48-1.8 μm (a), and of 1.04-1.65 μm (b). The excitation is at 1040 nm for (a) and 520 nm for (b).

4. CONCLUSIONS

In this work the temperature shift in the Sellmeier equation required for accurate calculations of the signal and the idler wavelengths in PPKTP OPO is studied in detail. It was found that this correction depends on the wavelength of the pump field. With the 532 nm excitation, a temperature shift of -26 °C should be applied in the Sellmeier equation, while with the 1064 nm excitation, a temperature shift of -18 °C should be introduced. The corrected Sellmeier equation fits well the available experimental data in the near-infrared and visible ranges. The results are expected to provide a more accurate reference for predicting the output wavelengths from the PPKTP OPOs pumped with fundamental wavelengths around 1 μm or with corresponding second harmonics. The derived temperature correction factors are not limited to the ultrafast and near-infrared OPOs, but can also be applied to the continuous-wave OPOs working in the visible to mid-infrared wavelength region. The reasons for this effect in general and its wavelength-dependent temperature shift in particular are not clear at the moment. Additional carefully designed experiments are needed to carefully derive the

Sellmeier equation and determine the cause of the temperature shift that has to be introduced in that equation when used to calculate the phase matched wavelengths.

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