Sellmeier and thermo-optic dispersion formulas for $CdSiP_2$

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High-accuracy Sellmeier and thermo-optic dispersion formulas for $CdSiP_2$ that reproduce excellently the temperature-dependent phase-matching conditions for the Tm:YALO and Nd:YAG laser-pumped optical parametric oscillator (OPO) are presented. © *2011 American Institute of Physics*. [doi:10.1063/1.3590136]

Owing to its large nonlinear optical constant ($d_{36} = 84.5$ pm/V) and high transparency in the $1.064 \sim 6.5$ μm range,[1,2] $CdSiP_2$ was found to be a superior material for OPO in the mid-IR.[2–4]

However, because the temperature dependent Sellmeier equations presented by Schunemann *et al.*[2] do not fit the 90° phase-matched OPO wavelengths given by Petrov *et al.*,[4] we have attempted to improve their Sellmeier equations to give the best fit to the 6.117 μm point at 25 °C[4] as well as the isotropic point ($n_o = n_e$) of 0.5143 μm given by Ambrazyavichus *et al.*[5] at 300 K.

The resulting Sellmeier equations at 25 °C are expressed as

$$n_o^2 = 11.4442 + \frac{0.65652}{\lambda^2 - 0.10464} + \frac{1286.198}{\lambda^2 - 617.005},$$
$$n_e^2 = 11.3443 + \frac{0.64705}{\lambda^2 - 0.11803} + \frac{1512.410}{\lambda^2 - 658.867}, \quad (1)$$
$$(0.514\ \mu\text{m} \le \lambda \le 6.117\ \mu\text{m}),$$

where λ is in μm.

This index formula is constructed by using the refractive indices of the homogeneous $CdSiP_2$ crystal grown by Schunemann *et al.*[1] and gives the phase-matching angle for type-1 SHG of 4.7846 μm (SHG of the CO_2 laser line at 9.5692 μm) at $\theta_{pm} = 43.13°$ which is slightly larger than the value of $\theta_{pm} = 42.3 \pm 0.1°$ given by Gonzalez *et al.*[6] While the index formula of Schunemann *et al.*[2] gives $\theta_{pm} = 43.00°$ at 25 °C. In order to simplify the calculation of the refractive index n and its derivative $dn/d\lambda$, we use the numerical forms $n^2 = A + B/(\lambda^2 - C) + D/(\lambda^2 - E)$ in our Sellmeier equations.

In addition, Eq. (1) gives the type-1 and type-2 phase-matching angles for SHG of 5.2955 μm (SHG of the CO_2 laser line at 10.5910 μm) at $\theta_{pm} = 42.77°$ and $\theta_{pm} = 76.47°$. The former agrees well with $\theta_{pm} = 42.46°$ given by the index formula of Schunemann *et al.*[2]

Figure 1 shows the phase-matching curves for type-1 OPO pumped by a $Tm{:}YALO_3$ laser at 1.993 μm together with the experimental points given by Schunemann *et al.*[2] The dashed lines (a) and (b) the theoretical curves calculated with the Sellmeier equations of Schunemann *et al.*[2] and the present authors, respectively. As shown in Fig. 1, the tuning curve calculated with our index formula is in agreement with their experimental points.

We next have formulated the thermo-optic dispersion formula for this material by using dn_o/dT and dn_e/dT deduced from the temperature dependent Sellmeier equations of Schunemann *et al.*,[2] and adjusted them to give the best fit to the temperature-tuned OPO curves presented by Schunemann *et al.*[2] and Petrov *et al.*[4] The newly constructed thermo-optic dispersion formula is expressed as

$$\frac{dn_o}{dT} = \left(\frac{1.1538}{\lambda^3} - \frac{1.1955}{\lambda^2} + \frac{0.7263}{\lambda} + 10.8238\right) \times 10^{-5}(°C^{-1}),$$
$$\frac{dn_e}{dT} = \left(\frac{1.3732}{\lambda^3} - \frac{0.6361}{\lambda^2} + \frac{0.8303}{\lambda} + 11.4051\right) \times 10^{-5}(°C^{-1}),$$
$$(0.5143\ \mu\text{m} \le \lambda \le 6.554\ \mu\text{m}), \quad (2)$$

where λ is in μm.

To verify the validity of our Sellmeier and thermo-optic dispersion formulas, we show the phase-matching curves for the temperature-tuned OPO pumped by Tm:YALO and Nd:YAG lasers together with the tuning curves calculated by the index formula of Schunemann *et al.*[2] and their experimental points (Figs. 2 and 3). As can been seen from these

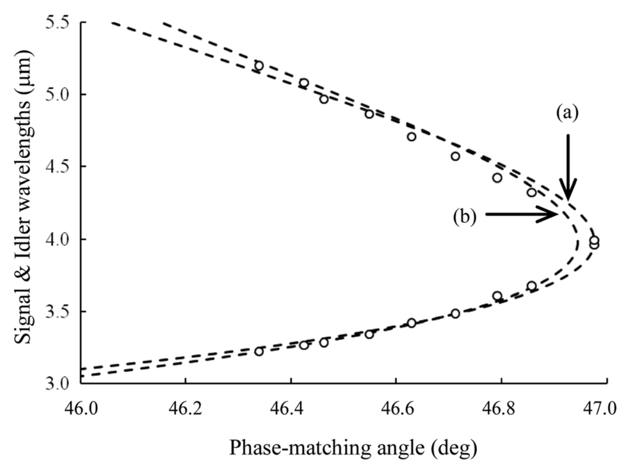

FIG. 1. Phase-matching curves for type-1 OPO pumped by a $Tm{:}YALO_3$ laser at 1.993 μm in $CdSiP_2$. The dashed lines (a) and (b) are the theoretical curves calculated with the Sellmeier equations of Schunemann *et al.* (see Ref. 2) and the present authors, respectively. ○: experimental points taken from Ref. 2.

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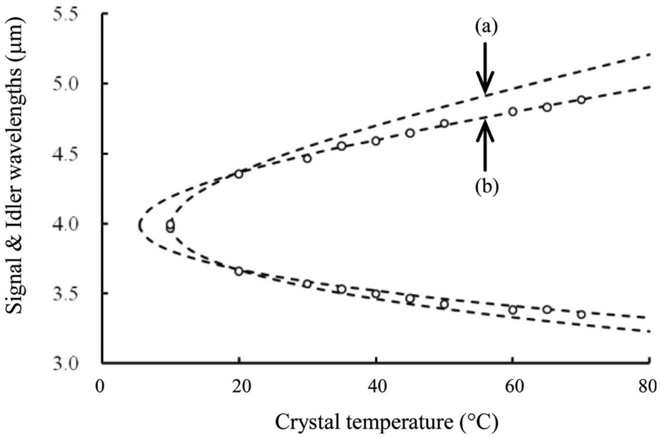

FIG. 2. Temperature tuning curves for type-1 OPO pumped by a Tm:$YALO_3$ laser at 1.993 μm in $CdSiP_2$. The dashed lines (a) and (b) are the theoretical curves calculated with the temperature-dependent Sellmeier equations of Schunemann *et al*. (see Ref. 2) and our index and thermo-optic dispersion formulas, respectively. ◯: experimental points taken from Ref. 2.

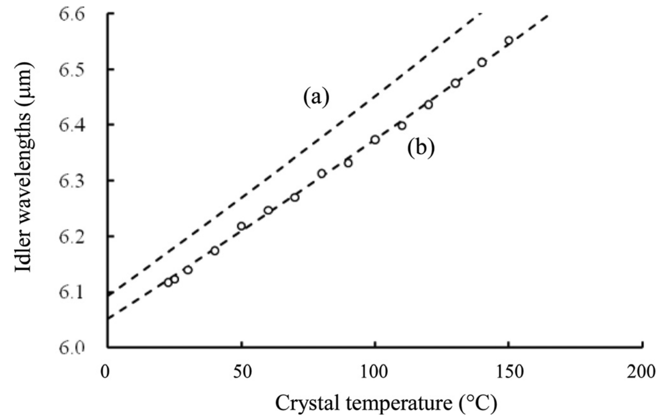

FIG. 3. Temperature tuning curves for Nd:YAG laser-pumped 90° phase-matching OPO in $CdSiP_2$. The dashed lines (a) and (b) are the theoretical curves calculated with the temperature-dependent Sellmeier equations of Schunemann *et al*. (see Ref. 2) and our index and thermo-optic dispersion formulas, respectively. ◯: experimental points taken from Ref. 4.

figures, our tuning curves give the perfect fit to the experimental points.

It should be pointed out that Eqs. (1) and (2) give the isotropic wavelengths of $\lambda = 0.5143$ μm at 300 K, and $\lambda = 0.4998$ μm at 77 K and $\lambda = 0.4950$ μm at 4.2 K, which are in close agreement with the experimental values given by Ambrazyavichyus *et al*.[5] at respective temperatures. In addition, we note that the temperature variations of the birefringence $d(n_e - n_o)/dT$ given by Eq. (2) agrees well the experimental points for the curve (3) plotted in Fig. 2 of Ref. 7, and hence the data points for the curve (4) should be read for $ZnGeP_2$ instead of $CdSiP_2$.

In conclusion, we have reported the high-accuracy Sellmeier and thermo-optic dispersion formulas for $CdSiP_2$. These formulas are believed to be highly useful for predicting the temperature-dependent phase-matching conditions, especially for the OPO pumped by the Cr:ZnSe laser operating at $2.2 \sim 2.7$ μm.[8]

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