Prediction of the Tuning Characteristics of an Optical Parametric Oscillator using Parametric Fluorescence*

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Knowledge of the tuning characteristics and generation efficiency of optical parametric fluorescence for a nonlinear crystal is of considerable help in defining the operational requirements of a tunable CW parametric oscillator. Detailed observations of the wavelength and temperature dependence of parametric fluorescence from crystals of barium sodium and lithium niobate are reported that extend for the first time to the infra-red. The merit of this approach is illustrated by comparing the temperature tuning curves of two operating argon pumped barium sodium niobate oscillators to the parametric fluorescence tuning curves of the same crystals.

One of the main problems in the design of an optical parametric oscillator (OPO) is the determination of the operating characteristics of a specific nonlinear crystal, since the optical properties of individual crystals differ considerably. The purpose of this paper is to report details of utilising parametric fluorescence data to establish optimum operating conditions of parametric oscillators and to predict their frequency tuning characteristics. Although parametric fluorescence measurements have been reported by other workers [1-5] their observations usually do not extend to wavelengths beyond 700 nm. Therefore in order to establish operating conditions for both degenerate and nondegenerate parametric oscillators it was necessary to extend fluorescence measurements to the infra-red. It is particularly useful when computer techniques are used to relate experimental to theoretical tuning data, since this allows optimum choice of a specific parametric pump, material and resonant structure for a desired spectral range under permissible operating conditions. Parametric fluorescence measurements can also be used to measure the bandwidth and gain coefficient of the parametric oscillator since the fluorescence emission is due to the parametric gain generated within a crystal by an intense laser pump beam [6, 7]. Hence, the conversion efficiency of the pump beam to low power fluorescence emission can be used as an indication of the available parametric gain of a potential parametric oscillator crystal. Therefore fluorescence measurements are helpful, in addition to a second harmonic generation test in selecting a specific nonlinear crystal for use in a parametric device.

The experimental arrangement necessary for obtaining parametric fluorescence data conveniently is the same as that for a parametric oscillator and therefore requires no additional apparatus. The apparatus that was used is shown in fig. 1 consisting of a CW argon laser or frequency doubled Nd:YAG laser, the crystal under investigation and a monochromator-photomultiplier system complete with phase sensitive detection. Since single pass amplification of phase matched parametric fluorescence emission is sufficient for making observations, the need for a parametric cavity structure is eliminated

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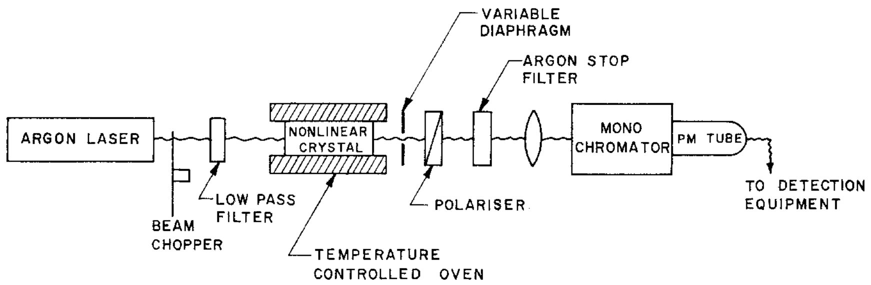

Figure 1 Schematic of the experimental arrangement.

which simplifies considerably the necessary optics and alignment procedures. By using recently improved photomultipliers (RCA types C31000J and C31000K) that are capable of spectral response up to 1 μ and beyond it was possible to obtain data up to the degenerate region for two convenient CW OPO pump sources: 514.5 nm and 488.0 nm (both from an argon laser). The photomultipliers were operated at $-60°$ C in order to minimise dark current and achieve optimum signal-to-noise ratios. It was also necessary to isolate the laser output with a short pass filter ($\lambda_c \sim 530$ nm) in order to eliminate numerous inherent fluorescence signals from the argon plasma. Since the bandwidth and strength of the parametric fluorescence emission depends on the acceptance angle of the detector [6], the fluorescence signal is passed through a variable iris diaphragm before being focused on the entrance slit of a monochromator. The optimum acceptance angle was found to be about 1.5 degrees. It is interesting to point out that by using a long narrow entrance slit, the recorded fluorescence signal becomes strongly asymmetrical with a sharp cutoff on the long wavelength side in contrast to the symmetrical signals reported in [6]. This can be explained by a spatial aperturing effect of noncollinear phase matched radiation that enters the spectrometer [8]. It turns out that the peak fluorescence signal does not correspond to the phase matched signal wavelength but lies at the half power point on the long wavelength side. This effect is useful in improving the accuracy of the parametric fluorescence data to about $\pm$ 2 Å.

The experimental temperature tuning data of fluorescence for three commercially available 90° phase matchable nonlinear crystals: barium sodium niobate, congruent (or "cold") and stoichiometric (or "hot") lithium niobate, is shown in fig. 2 obtained with an argon pump propagating as an extraordinary wave along the "*a*" axis of the crystal. From fig. 2 it is apparent that the temperature tuning range for $LiNbO_3$ crystals is considerably more restricted than for $Ba_2NaNb_5O_{15}$ crystals, since lithium niobate optically damages at temperatures below 165° C when pumped at a visible wavelength [9]. The high temperature limit of the fluorescence data was determined by the design of the optical oven and in the case of barium sodium niobate by a phase transition [3]. It is now possible to compare the experimental data to the theoretical

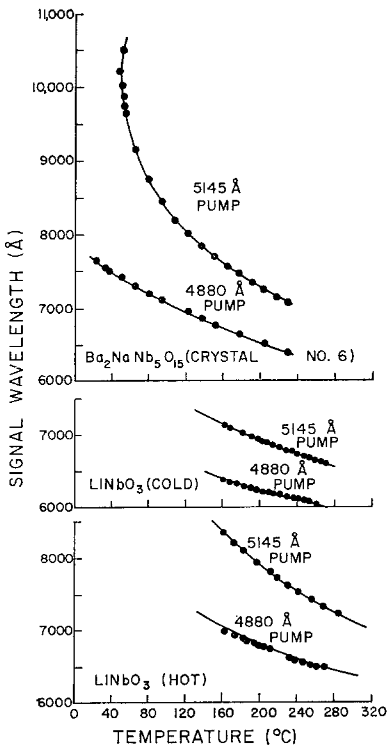

Figure 2 Experimental temperature tuning curves for parametric fluorescence from three potential OPO materials pumped with the two most intense argon laser lines.

tuning curve that is obtained by deriving the change in fluorescence wavelength with temperature from the collinear phase matching condition:

$$n_p^e(T)/\lambda_p = n_s^o(T)/\lambda_s + n_i^o(T)/\lambda_i \qquad (1)$$

where n_p^e, n_s^o and n_i^o represent the extraordinary and ordinary refractive indices for a given temperature T at the pump, signal and idler wavelengths λ_p λ_s and λ_i. By approximating n_s^o and n_i^o by Taylor's series to second order terms, we obtain for the variation of frequency for a given change in temperature

$$(\delta\omega)^2 = \eta\delta T \qquad (2)$$

where

$$\eta = \frac{(\omega_p/2)\ \partial/\partial T\ (n_p^e - n_o^o)}{\partial n_o^o/\partial\omega}$$

and n_o^o is the ordinary refractive index at the degenerate tuning point (ω_o, T_o). Fig. 3 shows a

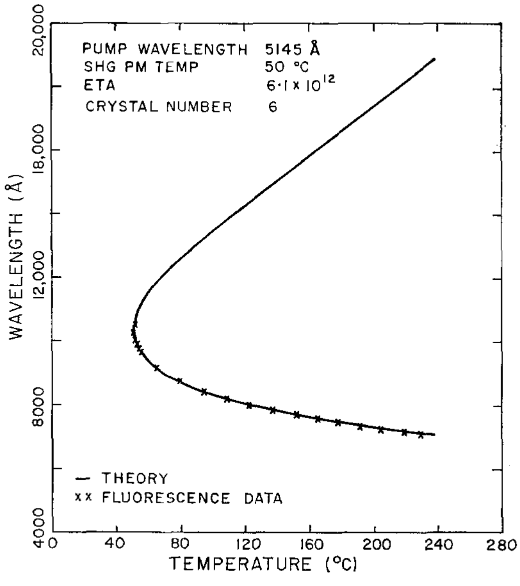

Figure 3 Computer generated temperature tuning curve of a typical barium sodium niobate crystal.

computer generated graph of the variation of a signal and idler wavelengths with temperature predicted from equation 2 by using published values of refractive index [10] and the actual phase matching temperature at degeneracy for the same barium sodium niobate crystal used to obtain the experimental temperature tuning curve in fig. 2. The subharmonic or harmonic phase matching temperature for a specific pump source and crystal is preferably determined experimentally for different crystals of the same kind. Otherwise it is also possible to compute the second harmonic phase matching temperature at a given wavelength by using an iterative technique if T_o is known at a nearby wavelength and $(\partial n^o)/(\partial\lambda)$, $(\partial n^e)/(\partial\lambda)$ and $\partial/\partial T(n_p^e - n_o^o)$ can be calculated. For direct comparison the theoretical dispersion data is fitted to the experimental fluorescence data. Of the six crystals that were examined in this manner, the phase matching temperature varied by as much as 30° C from crystal to crystal and the measured parametric fluorescence powers were an order of magnitude less than calculated values. This difference is due to pump and fluorescence losses that occur if the input and output faces of the crystal are not anti-reflection coated. Also some inaccuracies are introduced in the calculation of fluorescence power. For 5 mm long barium sodium niobate crystals the phase matched fluorescence power was of the order of 10^{-11} W at a pump level of 500 mW with an effective bandwidth of 1 nm, easily visible with the naked eye. Fig. 4 shows the

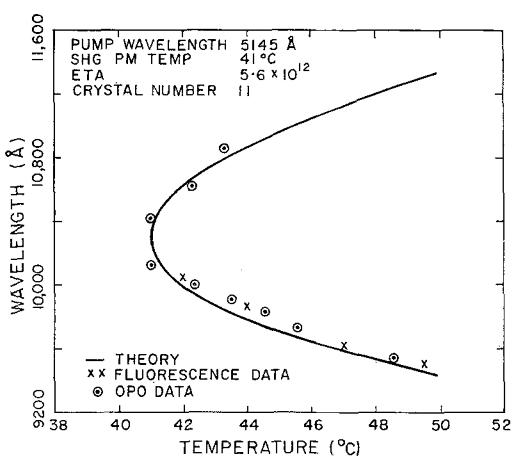

Figure 4 Experimental temperature tuning data of a degenerate argon pumped barium sodium niobate parametric oscillator superimposed on its parametric fluorescence tuning plot.

experimental tuning characteristics of an actual degenerate CW parametric oscillator superimposed on the predicted tuning curve obtained in the same manner as the curve shown in fig. 3. However, the crystal was not the same as the one employed in obtaining the data discussed in figs. 2 and 3. The tuning range of this specific OPO was limited to about 200 nm by the mirror transmission characteristics of the OPO reson-

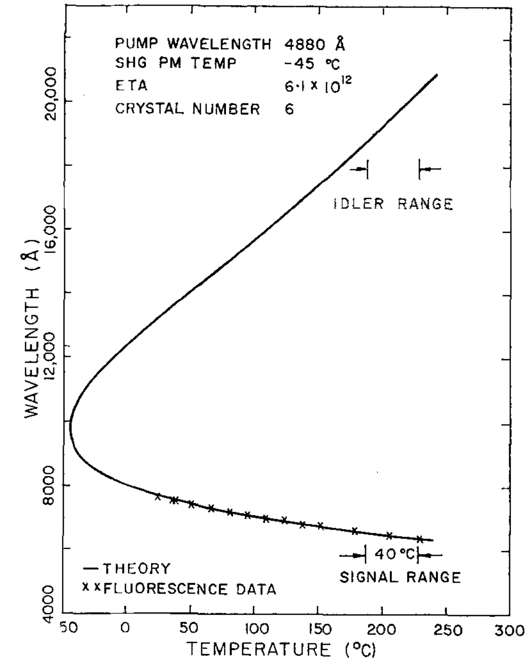

Figure 5 Parametric fluorescence temperature tuning curve of barium sodium niobate for a 4880 Å pump.

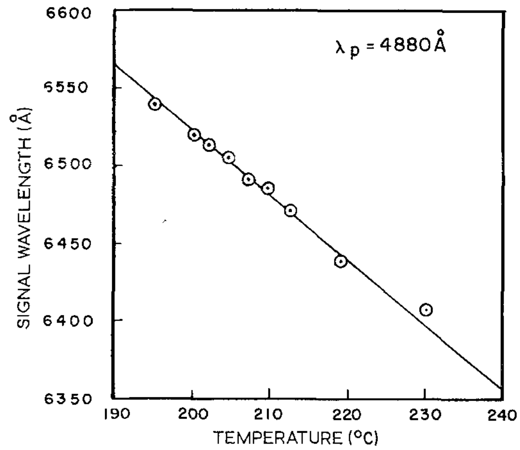

Figure 6 Experimental temperature tuning curve of a non-degenerate argon pumped barium sodium niobate parametric oscillator.

ator and the available single mode argon pump power. The threshold power required for onset of oscillations was 140 mW as compared to a calculated value of 50 mW. This discrepancy is partly due to pump reflection losses at the oscillator cavity input mirror and the fact that the "accidental" mode distribution of the cavity forces oscillations to occur at values that do not correspond to exact phase matching. For non-degenerate oscillators this parametric tuning technique becomes even more desirable, since extrapolation errors of theoretical tuning data increase with departure from degeneracy. Fig. 5 shows the parametric fluorescence tuning curve of a visible CW parametric oscillator that for the first time uses a barium sodium niobate crystal. The measured threshold is 200 mW and the signal wavelength tuning range as shown in figs. 5 and 6 is limited to 20 nm from 640 to 660 nm due to lack of broad band high reflective coatings in the visible range [11].

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