The origin of this damage process is now well understood (14). Both LN and BNN permit noncritical phase-matching for pump wavelength near 500nm.

For operation of OPO beyond 4μm, Te, Se, HgS, CdSe, Ag_3SbS_3, Ag_3AsS_3 are useful materials which are currently investigated.

BBO, KDP, ADP and their deuterated forms are the most promising materials for oscillators pumped in the ultraviolet which would be capable of tuning in the visible region of the spectrum. The primary limitations of KDP and ADP are their absorption bands beyond 1.2 μm, their relatively low nonlinear coefficients and the fact that they suffer from some form of optical damage induced by ultraviolet radiation (15-16). BBO is a new nonlinear optical material useful for frequency conversion at wavelengthes from ultraviolet to mid-infrared. Optical oscillation in BBO crystal with ultraviolet pumping are currently being investigated by many workers and will not be discussed here.

From table 3, using QPM in $LiNbO_3$ crystal has the advantages of the largest figure-of-merit (not include those crystals used in infrared), easy quasi-phase-matched in all transparency and relative high optical damage threshold (two orders of the damage threshold can be raised by doping with MgO). Thus the LN crystal with periodic domain structures will have great applications in OPA and OPO, and we will discuss the usefulness of QPM in optical parametric oscillation in detail in the following sections.

2. Optical parametric gain in QPM process

In any oscillator some form of gain is required to overcome losses and produce oscillation. This gain is produced by the interaction between electromagnetic fields in a nonlinear medium for parametric oscillation. In the parametric amplification process, a strong, high-frequency electromagnetic wave, called the pump, with a frequency ω_p, interacts via the nonlinear response of the medium with two lower frequencies, termed the signal and the idler, at the frequencies ω_s and ω_i respectively, to produce amplification at those two frequencies. The three frequencies are connected by the relation:

$$\omega_p = \omega_s + \omega_i \quad \text{or} \quad \omega_3 = \omega_1 + \omega_2 \qquad \ldots(5.1)$$

which implies energy conservation. The direction of the power flow, and hence the question of wether amplification or attenuation of the signal and idler occurs is determined by the relative phase between the pump and the product of the signal and idler fields. This phase in turn is determined by initial conditions. In the case of optical parametric oscillators which start from noise, the phase adjusts to produce gain. The principle interaction which adjusted by phase to oscillate is assumed to be phase-matched, i.e., satisfying the momentum coservation, leading to accumulative interaction, whereas the other interactions which are not phase-matched will be in general weak.

For QPM, the momentum conservation can be expressed as:

$$\vec{K}_3=\vec{K}_1+\vec{k}_2+\vec{g} \qquad ...(5.2)$$

where $\vec{g}$ is the reciprocal vector of the periodic domain structure in LN.

2.1. Parametric interaction in QPM process

We have proposed an effective expression for SHG of periodic structures: $p_{2w}/p^{o}_{2w}=I^2 x G^2$ (equation (1,4)). For the case of QPM, $I^2=1$ and G^2 has the value of $4/\pi^2$. Here p_{2w} is the second-harmonic output for QPM in $LiNbO_3$, p^{o}_{2w} is the output power of a perfectly phase-matched process in uniform crystal of equal length, i.e., the hypothetical e+e-->e type process using d_{33} in which it could be phase-matched by birefringence compensation in $LiNbO_3$ (in practical, this process can not be realized through birefringence compensation except in QPM). In general, the parametric process can be refered to as the inverse process of second-harmonic generation. Thus for the theoretical expressions of the parametric process in $LiNbO_3$ with periodic domain structures, we could present the expressions of the process simply, which is the same as the expressions for the hypothetical process aforementioned, in which only the factor of $4/\pi^2$ should be considered with the practical case of QPM. Then we can express the parametric interaction in LN with periodic domain structures in the general expressions, in which the nonlinear coefficient is $d_{eff}=2/\pi$

d_{33}. For caculating the tuning curves, only the energy and momentum conservations should be considered.

In the limitting case where TL << 1, the parametric gain of signal can be expressed as:

$$(Tl)^2 \frac{\sin^2(\frac{1}{2}\Delta k l)}{(\frac{1}{2}\Delta k l)^2} \quad \text{and} \quad T = \frac{16\pi^2 \omega_s \omega_i d^2}{n_s n_i c^2}|E_p|^2$$

where TL is an important quantity which shows parametric gain variation. For the same gain TL in cases of either using d_{31} nonlinear coefficient through birefringence phase-matching or using d_{33} through quasi-phase-matching, we have, $(TL)_{31}=(TL)_{33}$.

Thus $$L_{(33)} \approx \frac{1}{4} L_{(31)} \qquad \text{...(5.4)}$$

for the same pumping intensity I_3.

From equation (5.4), it can be seen that the effective interaction length of the crystal for QPM can be reduced about 4 times as comparing with the case of using d_{31}. The result has two meanings: the first is the nonlinear efficiency for same length of crystal can be greatly increased and the second is the threshold of pumping power can be greatly reduced for QPM in equal length of crystal.

2.2. Parametric oscillation threshold conditions

As mentioned above, the oscillation gain can be get in the process of the parametric interaction. In order to achieve oscillation the feedback in some kinds of form is required. In optical parametric oscillators, it is obtained by enclosing the nonlinear material in an optical resonator similar to that used in a laser. Although a number of different configurations of optical parametric oscillator existed, there are basically two types: Firstly, feedback is provided for both the signal and idler; This is called doubly resonant oscillator or DRO. Secondly, the feedback is provided for either signal or idler but not both. This type is refered to as a singly resonant oscillator or SRO.

For DRO, the threshold condition is found by requiring that the gain at the signal wave and idler wave can compensate for the round-trip losses at the respective ferquencies. letting the round-trip losses at the two frequencies be α_s and α_i, the threshold condition with the pump making a single pass through the crystal is given by(for small losses)

$$(\Gamma l)^2 \frac{\sin^2(\frac{1}{2}\Delta k l)}{(\frac{1}{2}\Delta k l)^2} \approx \alpha_s \alpha_i /4 \qquad \text{(DRO)} \quad ...(5.5)$$

For the SRO threshold is determined by requiring that the gain of the signal equals the round-trip loss α_s. Thus for small losses at the signal the threshold relation becomes

$$(\Gamma l)^2 \frac{\sin^2(\frac{1}{2}\Delta k l)}{(\frac{1}{2}\Delta k l)^2} \approx \alpha_s \qquad \text{(SRO)} \quad ...(5.6)$$

The pump-power density required to achieve threshold may be found from the above equations. In the limit of small losses the threshold pump-power densities are given by

$$S_p^{th} = \frac{\alpha_s \alpha_i}{4\pi K l^2 (1-\delta^2)} \left[\frac{\sin^2(\frac{1}{2}\Delta k l)}{(\frac{1}{2}\Delta k l)^2} \right]^{-1} \qquad \text{DRO} \quad \ldots(5.7)$$

for the DRO and

$$S_p^{th} = \frac{\alpha_s}{\pi K l^2 (1-\delta^2)} \left[\frac{\sin^2(\frac{1}{2}\Delta k l)}{(\frac{1}{2}\Delta k l)^2} \right]^{-1} \qquad \text{SRO} \quad \ldots(5.8)$$

For the SRO, when d_{33} nonlinear coefficient is used. $K=8\omega_0^2 * d_{33}^2/n_s n_i n_p * C^3$, $\omega_0=1/2\omega_p$ is the degenerate frequency and measures the deviation of the operating point from degeneracy (i.e., $w_s=w_0(1+\delta)$ and $w_i=w_0(1-\delta)$). It is seen from these expressions that the pump-power density required to achieve threshold is inversely proportional to the square of the crystal length or the number of periodic domain laminas, inversely proportional to the square of nonlinear coefficient and directly proportional to the product of the three indices of refraction. The increase in threshold pump-power density resulting from momentum mismatch is clearly evident. Comparing the two above equations, it is also seen that the threshold pump-power density for the SRO is a factor of $4/\alpha_i$ greater than that of a DRO with the same loss at the signal.

Because the interacting length could be greatly reduced when using quasi-phase-matching method, aperture effect may not be considered here though it is existed. The effect of finite beam size or the optimum degree of focusing are only limitted by diffraction of light or the natural tendency of a beam to spread. So the effect of beam size (for the case of Guassian beam) also might not be considered in the case when using QPM technique. A theoretical analysises of the effect of finite beam size and the aperture effect can be given out and will be improve our discussion given here, but it will ommited for simplicity.

2.3. Phase matching

Parametric gain for the coupled waves is seen to be critically dependent upon the amount of momentum mismatch between the three waves. From above equations of parametric threshold conditions and the gain, materials in which dispersion is not zero and Δk may be large, may have a small parametric gain. Several schemes have been realized to compensate for the effects of dispersion including the use of birefringence, noncollinear interactions, guided waves, phase reflection at boundaries, and contribution to the index of refraction due to free electrons in a magnetic field.

We firstly proposed here the quasi-phase-matching scheme for the optical parametric oscillation in $LiNbO_3$ crystals with periodic domain structures. By using d_{33} nonlinear coefficient through QPM technique, the optical parametric oscillator will be more efficient, of higher powers and greater tuning ranges.

3. Calculations of the relations between three frequencies and the coherence length

Suppose that in a real atomic system, polarization induced in the medium is not proportional to the optical electric field, but can be expressed as a Taylor series expansins as

$$P_i=\varepsilon_0\chi_{ij}E_j+2d_{ijk}E_jE_k+4\chi_{ijkl}E_jE_kE_l+\ldots\ldots \quad \ldots(5.9)$$

Limitting our attention to the second-order terms in above equation, that is

$$P_i=2d_{ijk}E_jE_k \quad \ldots(5.10)$$

For $LiNbO_3$ which has a 3m point-group symmetry, we can deduce two kind of nonlinear processes in using either d_{33} or d_{22} (using QPM technique in the LN crystal with PDS):

$P_z=2d_{33}E_z{}^sE_z{}^i$ (e—ee)

$P_y=2d_{22}E_y{}^sE_y{}^i$ (o—oo)

Though d_{22} nonlinear coefficient is relatively small as comparing with d_{31} in $LiNbO_3$. But it is 6-7 times larger than d_{36} of KDP. It corresponds to the crystal grown along c-axis (the growth of LN crystal along this direction is relatively easier than that along the a-axis) and can also be used in entire transparent range of $LiNbO_3$ crystal theoretically. The consideration of this case is important for using the crystal grown along c-axis to verify our theorectical analysis about the OPO through the QPM process.

3.1. Calculations when using d_{22} nonlinear coefficient

In the transparent range of $LiNbO_3$, 0.35 to 4.5μm, we have calculated the tuning curves when using d_{22} in QPM technique, but here the tuning curves are not in its original meaning. They are not the relation between the two generated frequencies and the crystal rotation angle or the operating temperature, but are the relation between the two frequencies and domain period in $LiNbO_3$. For different pumping waves(or fundamental waves), 400, 440 and 532nm, we get the calculation results shown in figure 1 to 3. These figures give the information of the relation between the two generated ferquencies and the period of domain structures, i.e. the tuning range . It is easily seen that, the tuning range near degenerate frequency is very large. The typical merit of the oscillator is very high angular sensitivity near degeneracy. In all these considerations, the most important are as follows: firstly, the minimum period of laminar domains is not less than 1.5μm, which means the growth of $LiNbO_3$ crystal with applicable periodic laminar domain structures is possible, and secondly, the available tuning range in short wavelength side in which tuning of frequency is impossible with single domain $liNbO_3$ crystal through birefringence phase-matching.

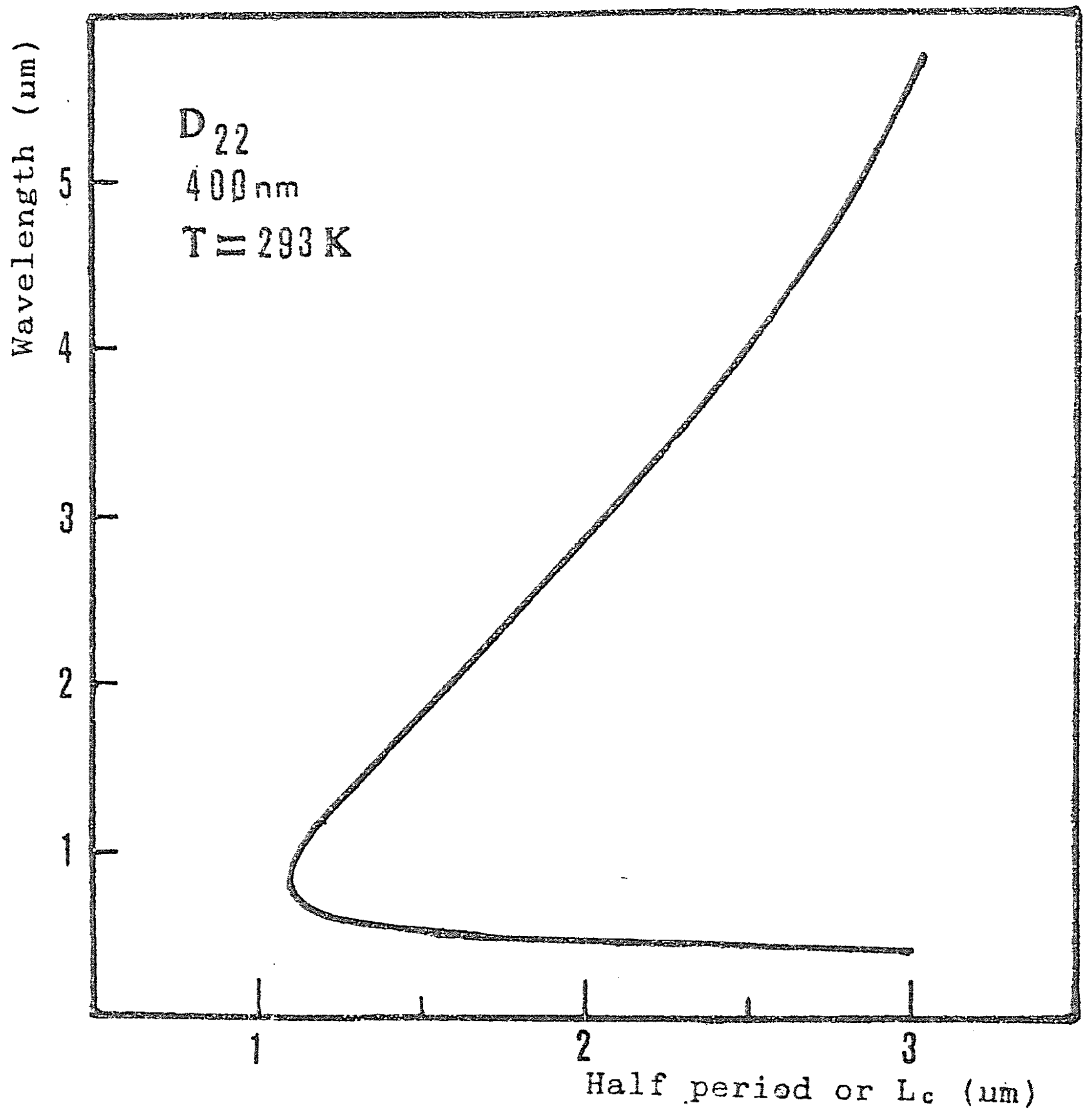


Fig. 1. Tuning curve at pumping wavelength 400 nm using d_{22}

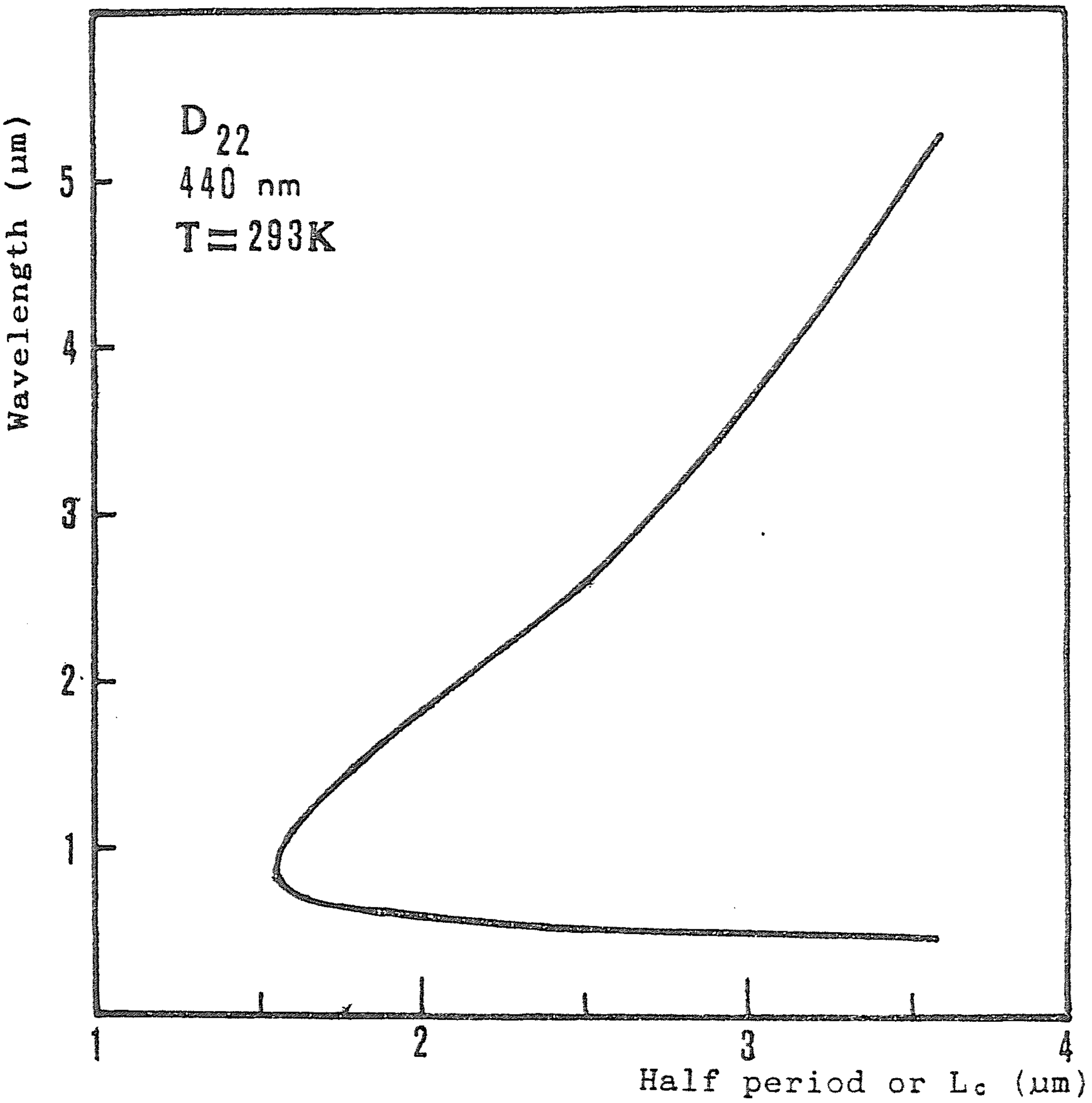


Fig.2. Tuning curve at pumping wavelength 440 nm using d_{22}

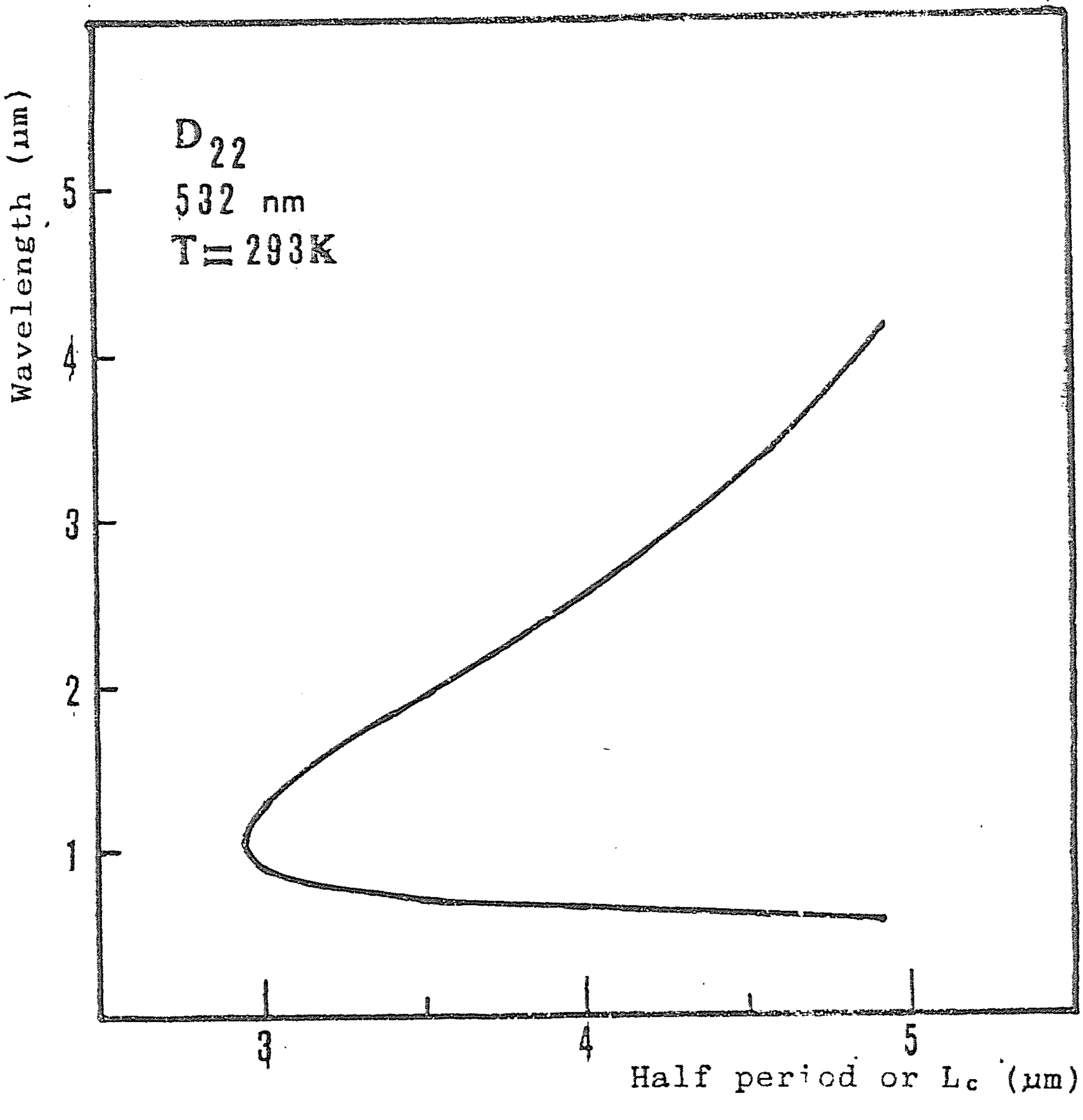


Fig.3. Tuning curve at pumping wavelength 532 nm using d_{22}

3.2. Calculations when using d_{33} nonlinear coefficient

Using QPM technique, the largest nonlinear coefficient d_{33} now is usable. Two important characteristics are existed here: The tuning range of this kind of oscillator could cover the entire transparency range of $LiNbO_3$ and secondly the efficiency of the parametric interaction could be greatly improved.

The calculations when d_{33} is utilized are similar to that of using d_{22}. Figure 4 to 8 show the variations of frequencies of signal and idler with the period of laminar domain structures at different pumping frequencies: 400, 440, 460, 532, and 1064nm. Figure 9 to 11 show the dependence of the tuning range with different given periods of laminar domains at different pumping frequencies. In these figures, we have supposed in our calculations that the rotation angle of the LN crystal sample with PDS is about 30°. The results shown in these figures are:

1). For a given LN sample with periodic laminar domain structures, we can get different tuning range at different pumping frequencies. For example, when the period is 2.0 μm, the tuning range is between 470 to 490 nm for 400nm pumping, but it is between 590 to 670 nm for 440 nm pumping, as shown in figure 9.

2). As we have mentioned before that the effective length of crystal for the same parametric oscillation gain can be greatly reduced as using of QPM technique, therefore when the pumping frequency is down to 400nm or even lower, the absorption and thermal loading can be reduced too.

3). Optical damage threshold can be raised by dopant in LN crystals with periodic domain strutures. This increses the possibility of its applications in short wavelength in which more resistanse to optical damage of crystal is required.

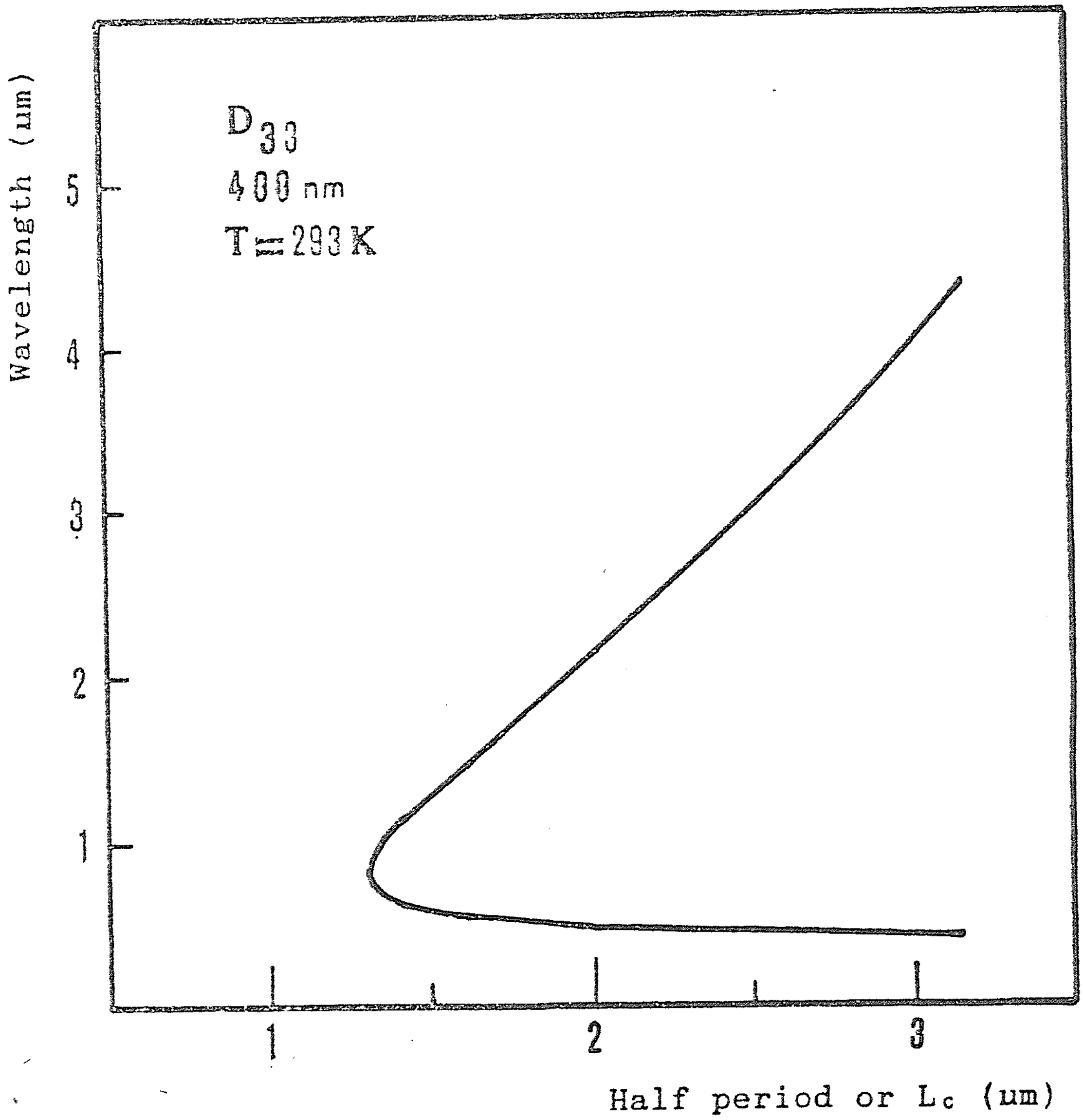


Fig.4. Tuning curve at pumping wavelength 400 nm using d_{33}

4). The angle sensitivity of the oscillator is very high when near the degeneracy and becomes lower when it locates apart from this degeneracy. It is able to choice a suitable angle sensitivity in practical applications.

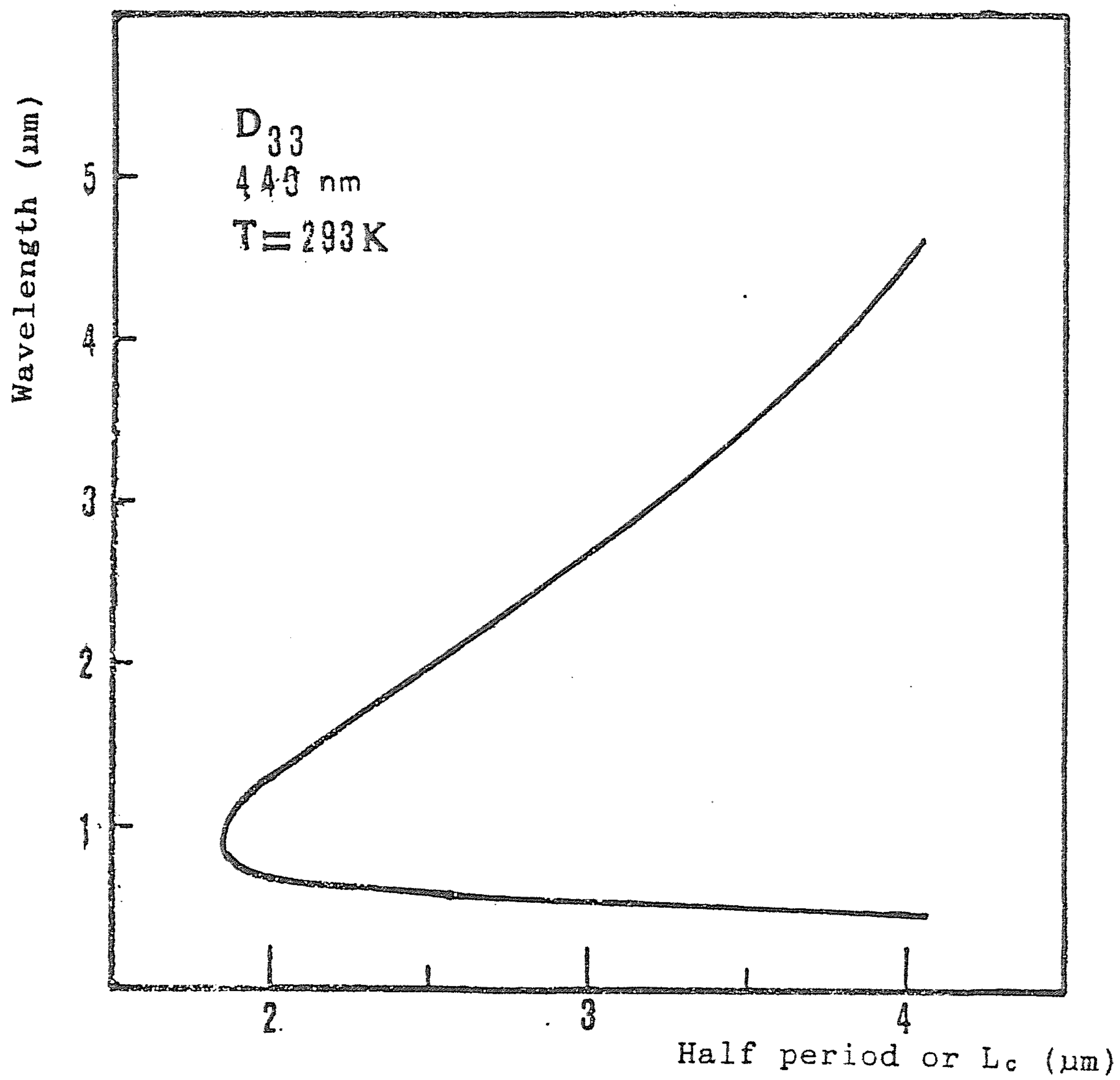


Fig.5. Tuning curve at pumping wavelength 440 nm using d_{33}

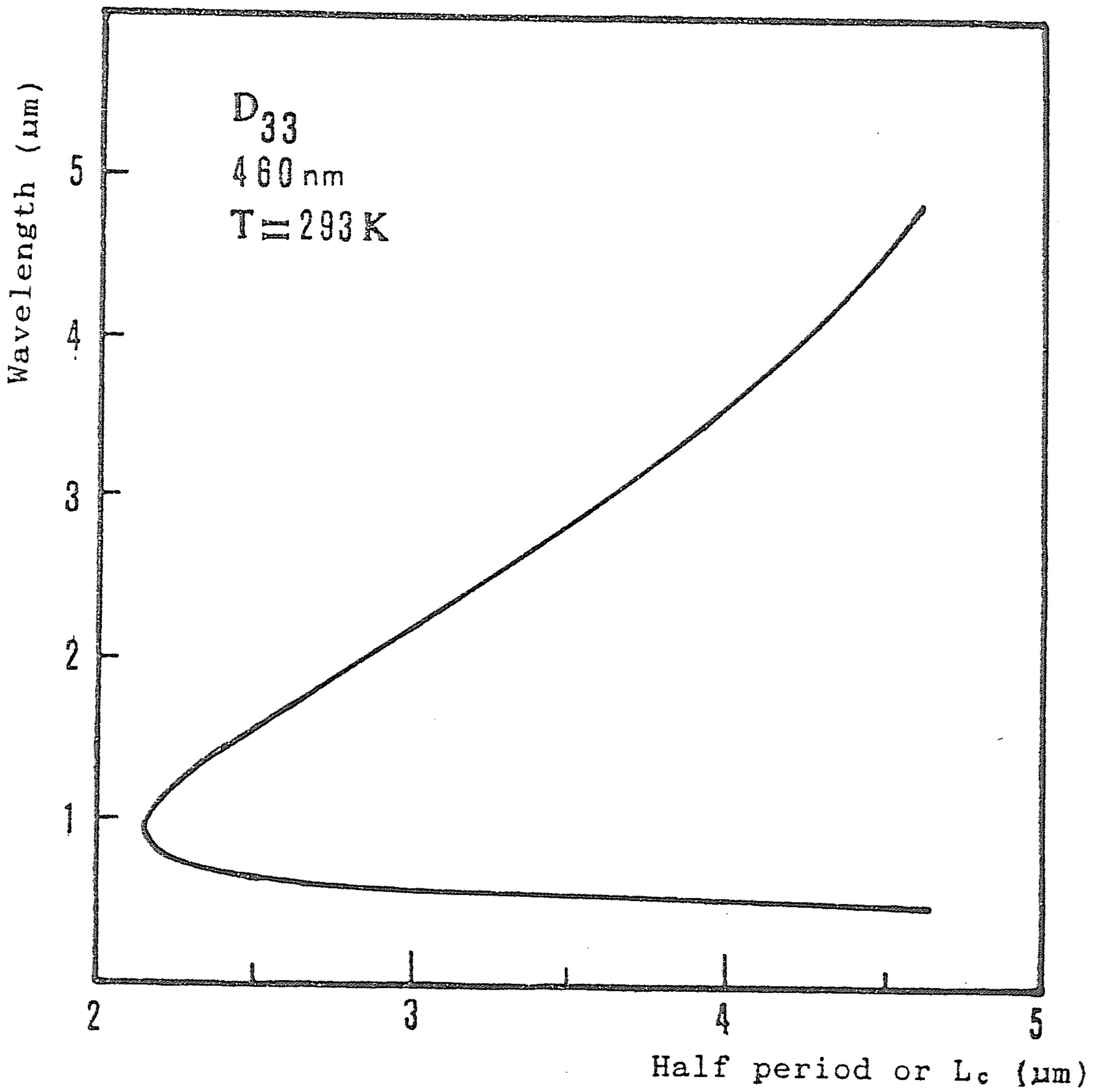


Fig.6. Tuning curve at pumping wavelength 460 nm using d_{33}

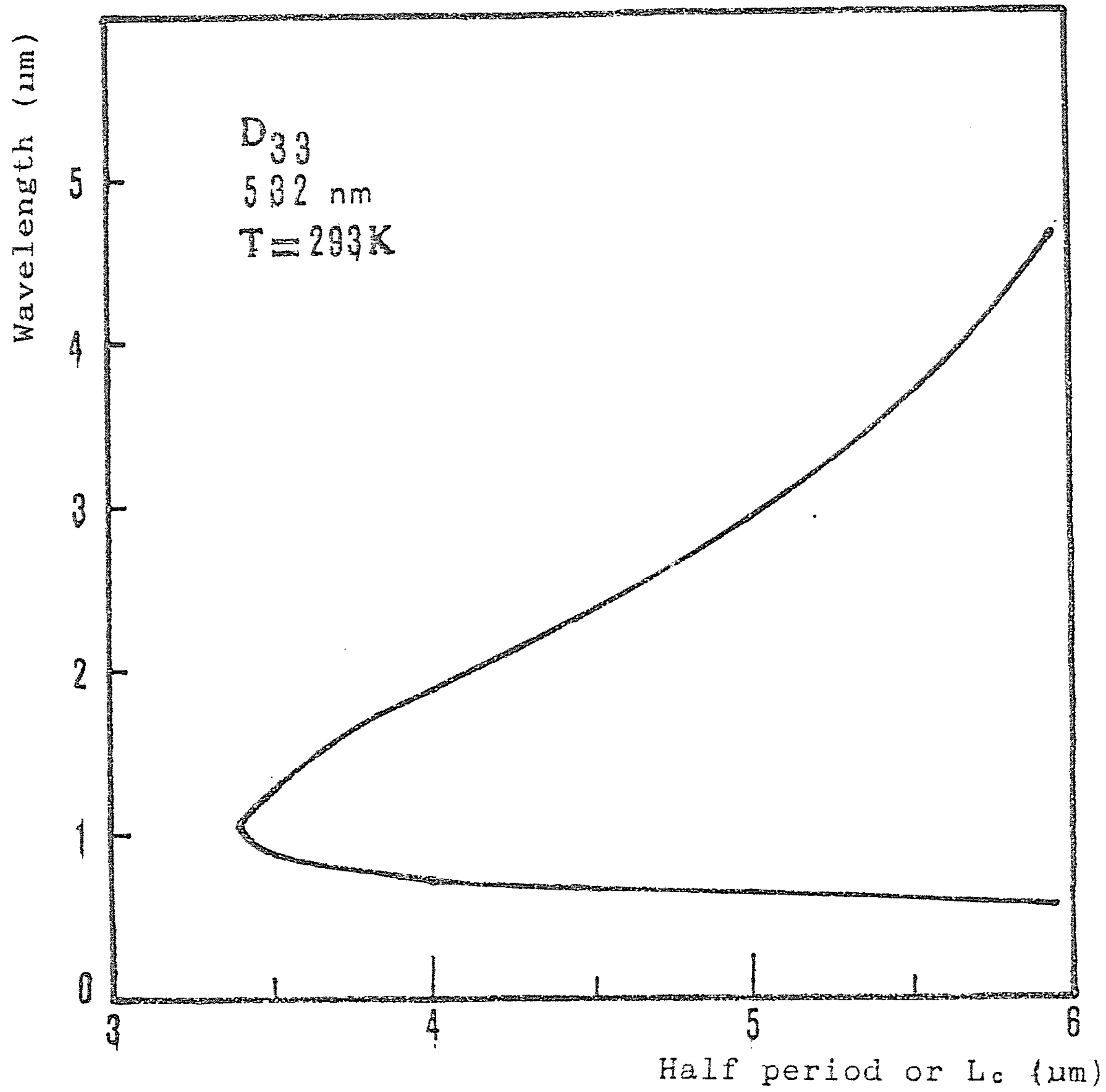
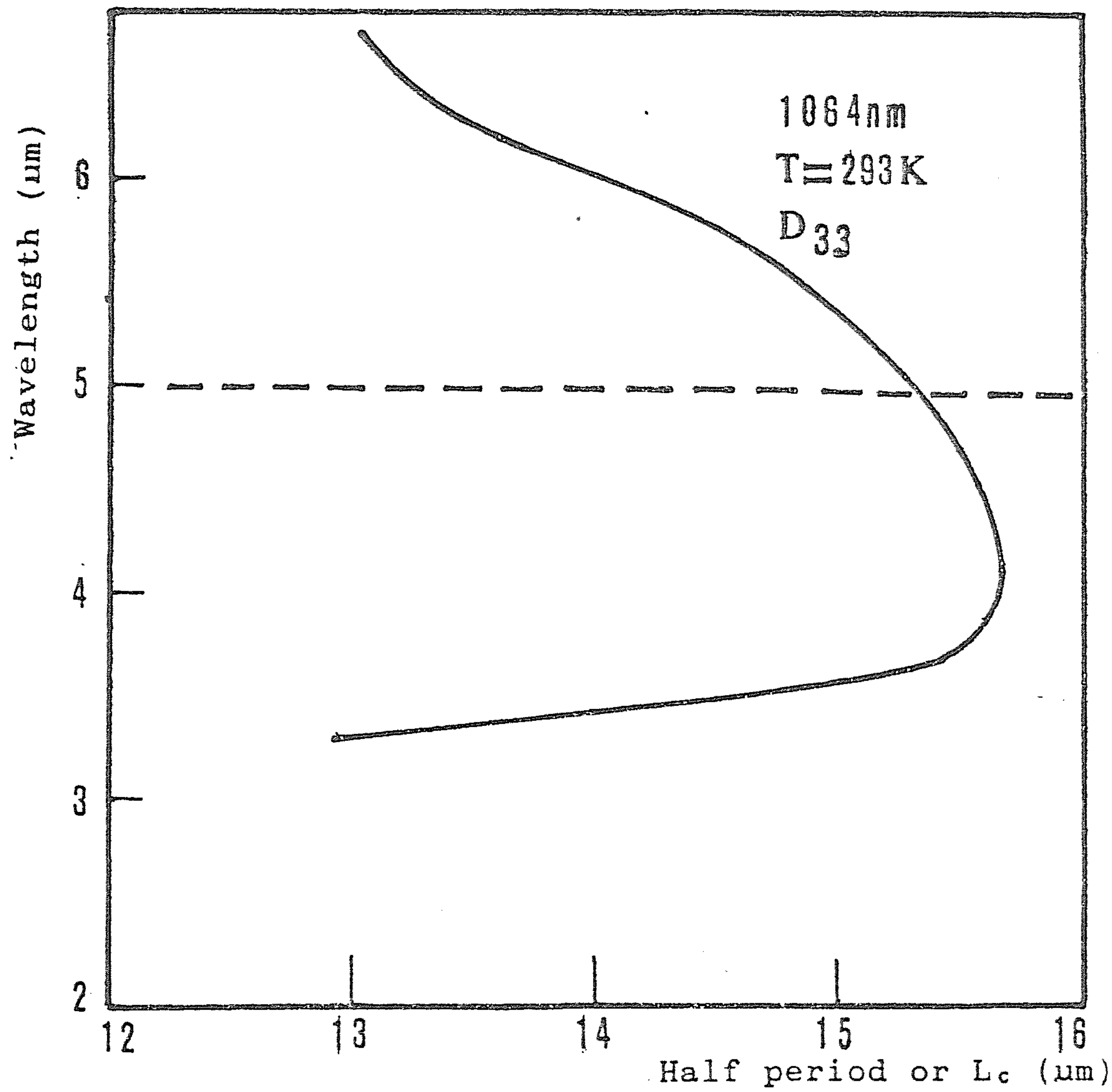


Fig.7. Tuning curve at pumping wavelength 532 nm using d_{33}



33

Fig.8. Tuning curve at pumping wavelength 1064 nm using d_{33}

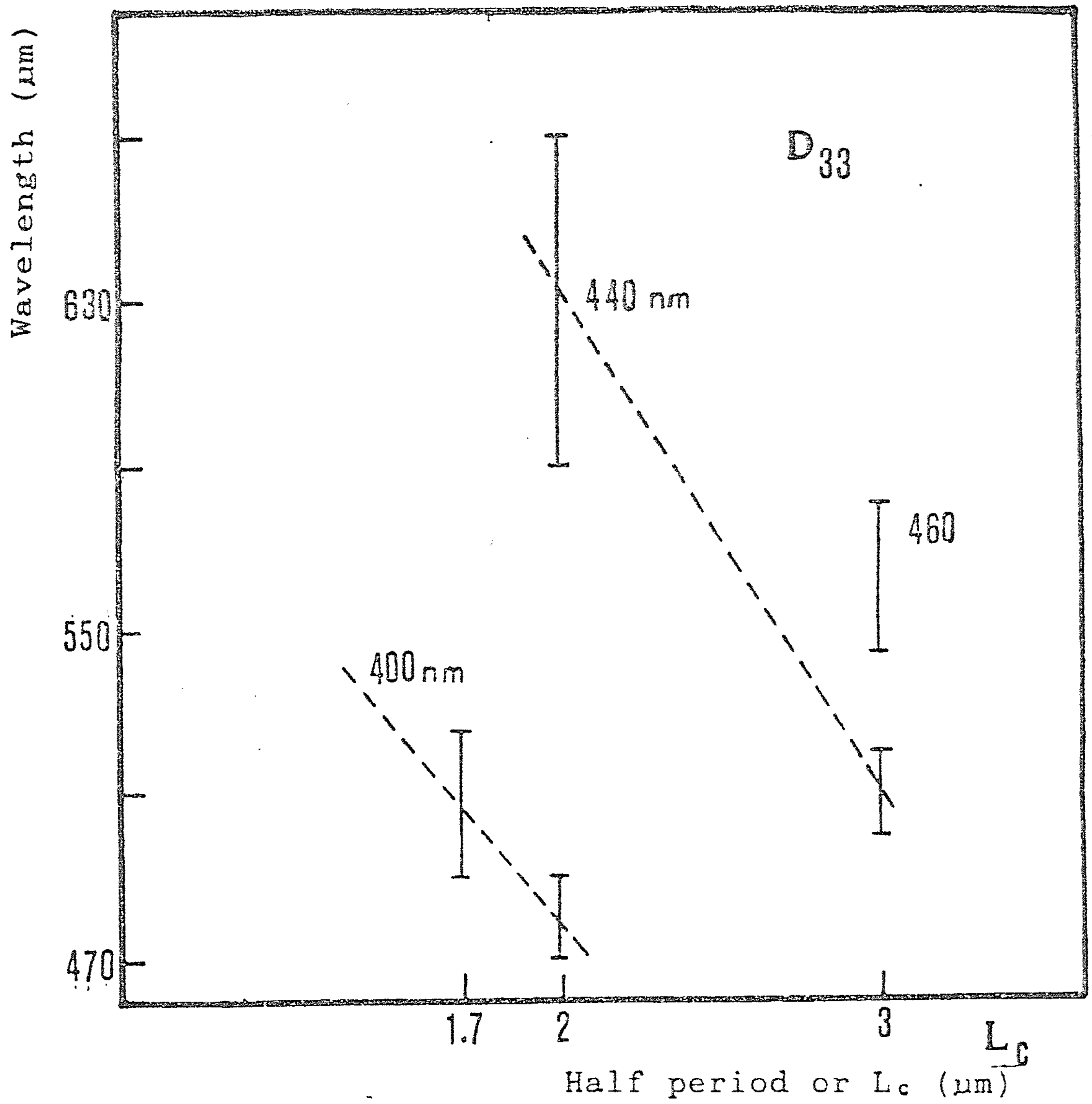


Fig.9. The relationship between tuning range and coherence at pumping 400,440 and 460 nm using d_{33}.

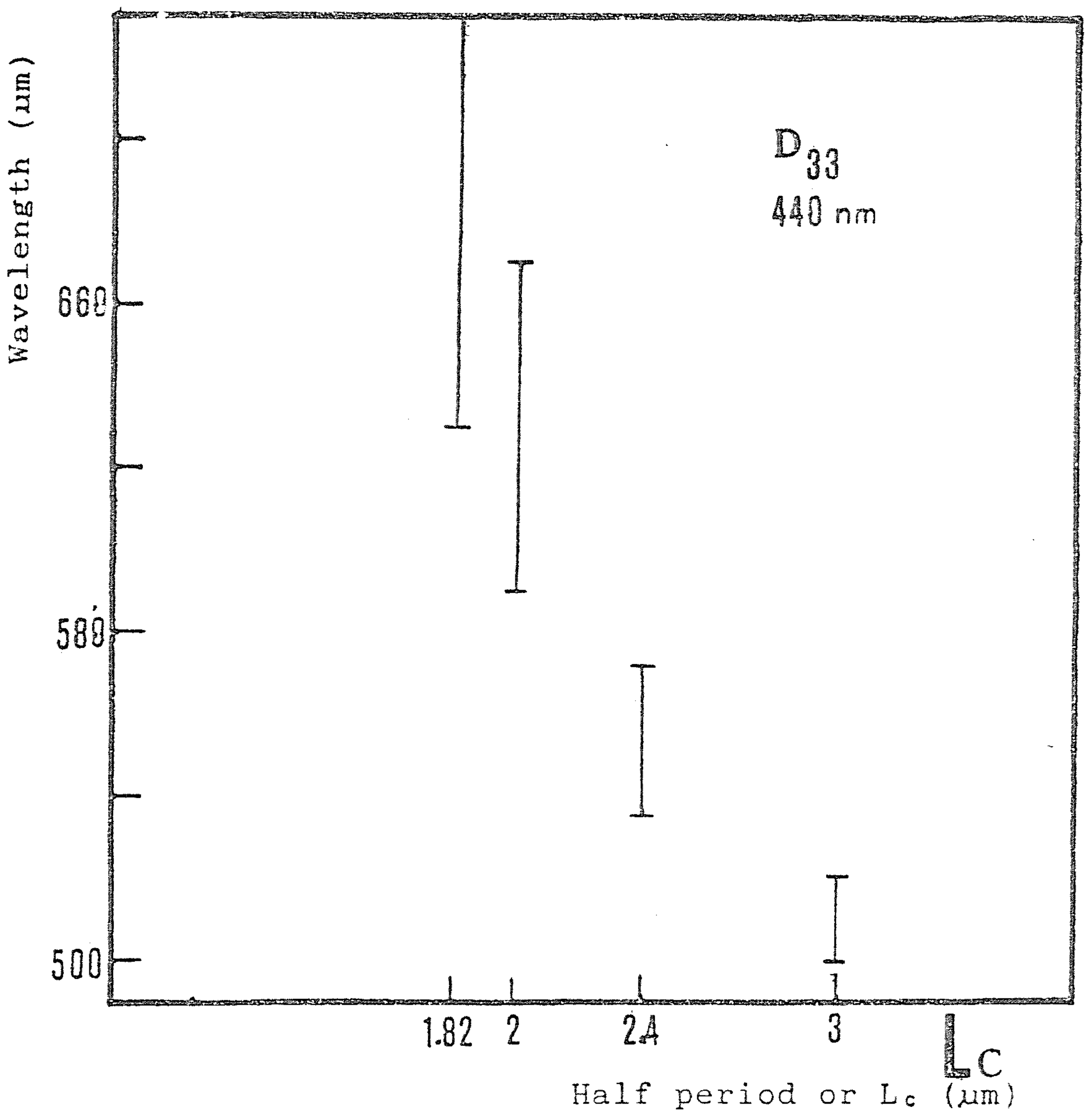


Fig. 10. The relationship between tuning range and coherence length at pumping 440 nm using d_{33}

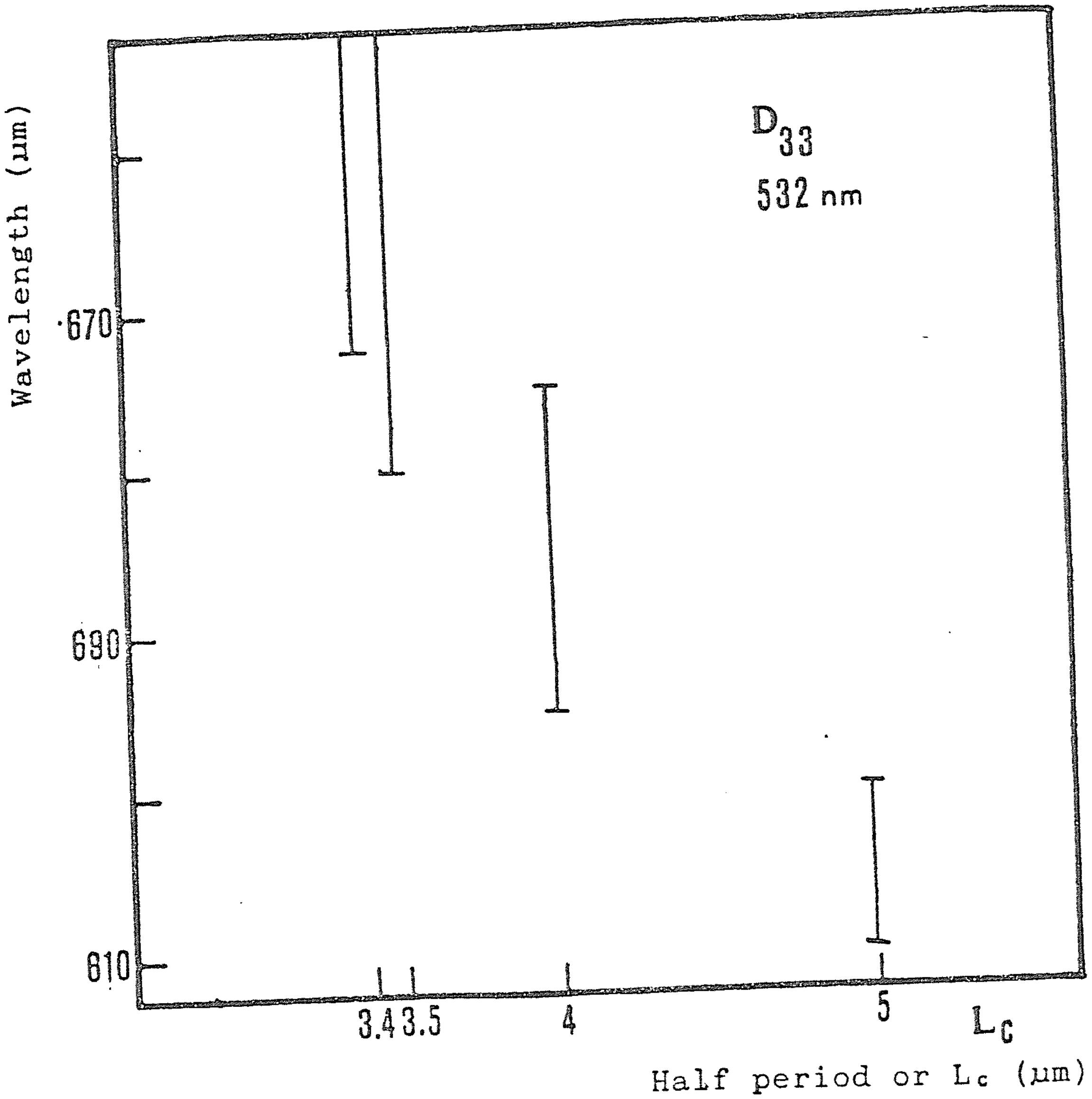


Fig. 11. The relationship between tuning range and coherence length at pumping 532 nm using d_{33}.

In figure 8 the pumping frequency is 1064nm, and the degeneracy point sits opposite side as comparing with figure 4 to figure 7. There might have some interesting variations when pumping frequency changes from 532 to 1064nm. We have shown this change in figure 12. From this figure, it is seen

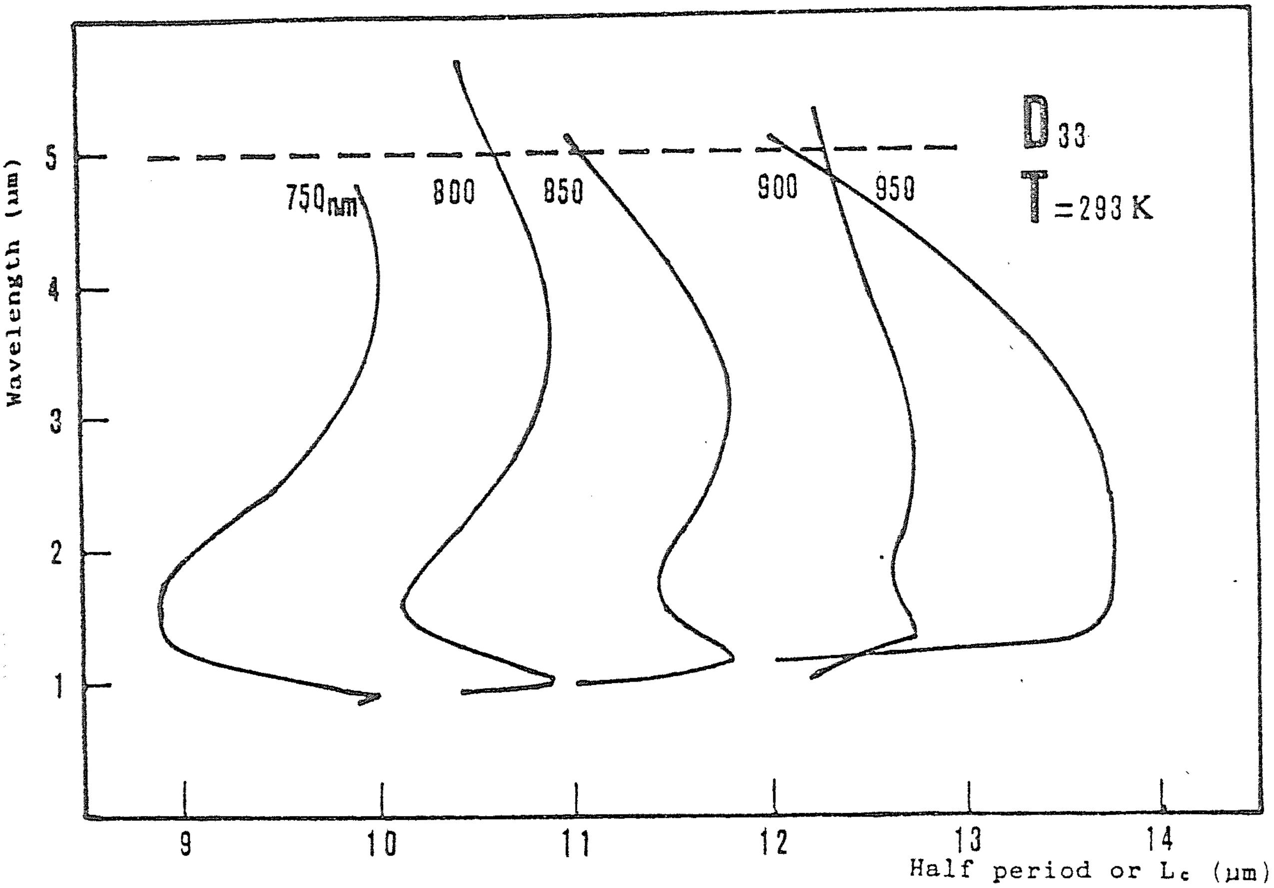


Fig.12. The variation of the tuning curves in changing the pumping frequency from 750 to 950 nm.

that there really existed an interesting transition range which is from 750 to 900 nm and the corresponding value of the half of the domain period is from 10 μ to 13 μ. In this period, there existed an important phenomenon that, for given pumping frequency, there existed a scope of domain period in which there are two groups of frequencies which abide the momentum conservation, i.e. in some pumping threshold, it could generated two groups of signal and idler waves through parametric interaction. This new nonlinear optical phenomenon is firstly predicted here and we shall verify it in our further experiments.

3.3. Tuning

In general operation of an optical parametric oscillator, it will tend to oscillate for those frequencies for which $\Delta K=0$. These frequencies are refered to as w_{so} and w_{io}. By varing the pumping frequency or the indices of refraction of the crystal or the angle between the three waves for a noncollinear interaction, the frequencies w_s and w_i satisfying the conservation equations and hence the operating point of the oscillator can be varied. The indices of refraction of the crystal may be varied by changing the crystal temperature, by varying the propagation direction with repect to the crystal axes, by applying an external electric field or strain forced on the crystal or by some combination of these methods.

According to our previous calculations, a new tuning method is proposed here. We change the period of laminar domain structures by rotating the crystal with a given rotating rate. The tuning curve is conveniently charaterized by a degeneracy parameter, δ , defined by

$$\delta=(\omega_{s0}-\omega_0)/\omega_0=(\omega_0-\omega_{i0})/\omega_0$$

where $\omega_0 = \frac{1}{2}\omega_p$ is the degeneracy frequency. The tuning curve is then a relation of the form

$$f(\delta, l_c, T)=0 \qquad ...(5.11)$$

where l_c is coherence length and T is the temperature.

In this relation, the rate of tuning $d\delta/dl_c$ is more rapid near degeneracy and blows up as $\delta \to o$. Aside from providing a rapid tuning, it presents two major problems: first of all to operate at a particular frequency near degeneracy the accuracy with which l_c must be set is high. Secondly operation near degeneracy results in potentially large oscillation linewidth.

As we have aforementioned, rotating the sample to change the period of laminar domain structures, there exists a tolerance angle beyond which the efficiency will decrease greatly. In our previous experiments, this tolerance angle is about 10° for the sample with no antireflection. But with antireflection coating on sample and with good periodicity of domains, it is possible to increase the angle to about 30°, as we have used in abtaining the above figures.

If l_c is given, and only the temperature at which the oscillator used could be changed, the tuning curve becomes

$$f(\delta, T)=0 \qquad ...(5.12)$$

In either the DRO or the SRO, the oscillation occured in three modes where the largest net gain can be seen and for which ΔK is smallest. By changing the crystal's temperature, a new method of tuning is achieved.

Figure 13 to 14 show the correspondence between signal wavelength and temperatures at pumping wavelength of 400nm and 532nm respectively. The variation for for different period of laminar domain structures are shown in these two figures too. At a given pumping wavelength, for example, 400nm, short l_c has large temprature tunnability. The emission of shorter wavelength is at the expense of temprature tunnability.

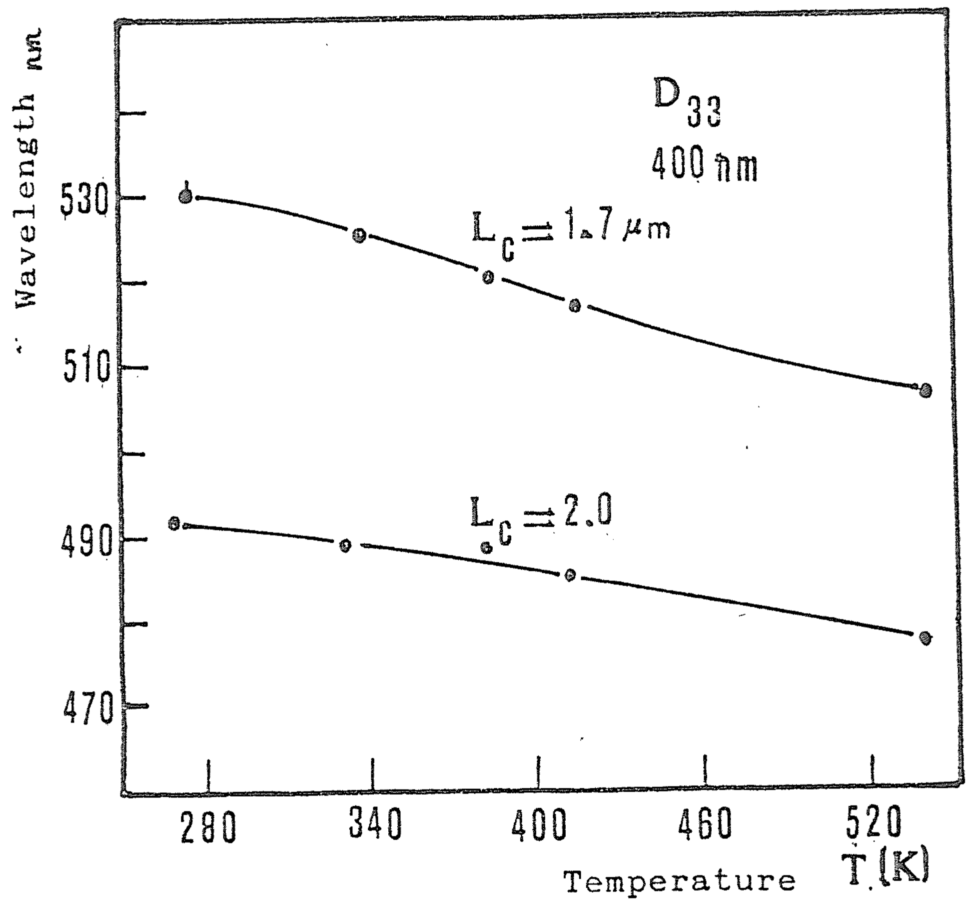


Fig. 13. Temperature tuning for different half of the period or L_c at pumping 400 nm.

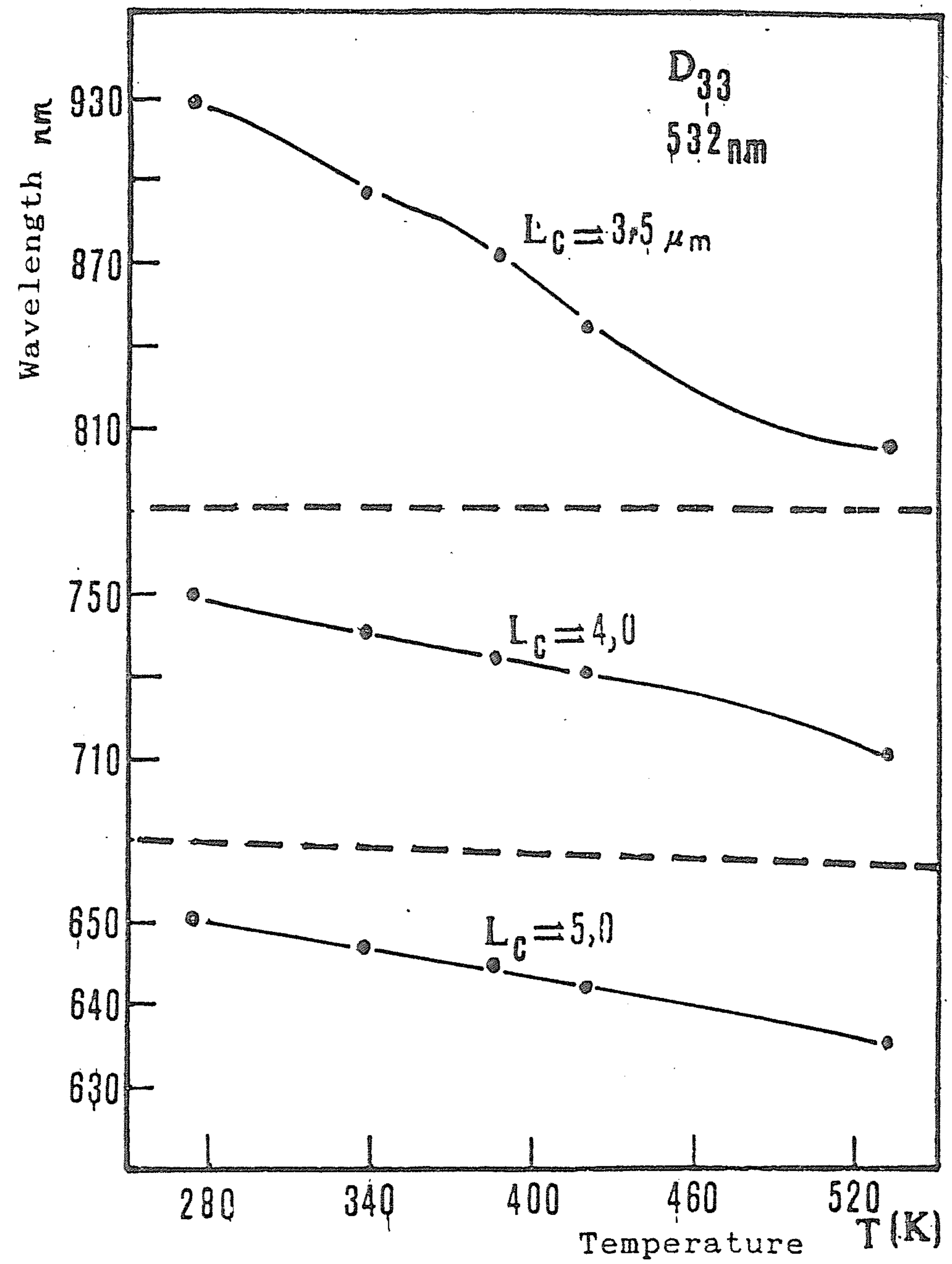


Fig. 14. Temperature tuning for different half of the period or L_c at pumping 532 nm.

In conbination of the two tuning methods: temperature tuning and angle tuning, a much large tuning range in the region of blue or green spectrum in QPM $LiNbO_3$ OPO could be obtained. It shows that the practical applications of this kind of optical parametric oscillator is possible.

The theoretical analysis of OPO using QPM technique in this chapter is of importance in constructing a OPO with high efficiency, large tuning range, and operation in short wavelength spectrum. The experiments for verifying this theory in the preparation.

4. Conclusion remarks

In this chapter, we have proposed the QPM technique in OPO firstly. A detail discussion about the QPM process in OPO in LN crystal with PDS is given. The calculation of the tuning curves of the OPO have been given in the process of o+o--->o and e+e--->e processes in which the d_{22} and d_{33} nonlinear coefficient were used respectively. We have also proposed a new tuning method of the OPO which is achieved through the changement of the period of the domain structures by rotating the sample. The relationship between the tuning range and the pumping wavelength have been shown in this chapter.

The OPO proposed has the main characteristics as follows:

a). It is high efficient and low pumping threshold.

b). It can be operated in the range of blue or blue green spectrum in which the single domain LN can not be used. The LN crystal can be phase matched through QPM in its entire transparency range.

c). It is easy to choice the operating angular sensitivity and tuning range by adjusting the pumping wavelength and the period of domain structures.

d). It has large tuning range.

e). It has high damage threshold with the choiced dopant in LN crystal.

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POSTSCRIPT

Optics is making rapid inroads into application areas previeously dominated by electronics. Led by fiber communication systems, optics is being given serious consideration for applications where band-width and electrical interference are presenting severe limitations on electronics. Such applications are supercomputering where efforts for increasing performance are beginning to turn toward the interconnection of many microprocessors rather than trying to attain a single superprocessor. The importance of communications in these new multiprocessing architectures has focused attention on optics to provide the necessary bandwidths. Opto-electronics and/or integrated optics are actually important in future man'life. However, materials limitations are significantly slowing the development of required optical devices. The chief limitation is the non-existence of device quality materials exhibiting a large nonolinear response. This includes needs for both second and third order nonlinear materials.

The work in this thesis is just at the beginning of the area, we should or can make greater progress in the aera of opto-electronics and its applications.

Acknowledgements:

I am indebt to prof. N.B.Ming who given the encouragement not only in the three year's research on science, but also in my three year's life in Nanjing University. His elaborate scientific spirit and his amiableness will be in my mind forever.

I am grateful to prof. Z.J. Yang for his tremendous amount of time and effort for helping during my doctorate period, to L.Mao and S.D. Chen for our brotherly cooperation, to Y.T.Lu of Shanghai Institute of Optics and Fine Mechanics for his kindly cooperation in our experiments. to the collegues in the Lab. of Crystal Growth and the Lab. of Solid State Microstructures.

I shall present the thesis to my parents and to my wife, W. Q. Gao, for their spiritual encouragement and substantial support.

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6). The applications of LN crystal with PDS for nonlinear optical frequency conversion.

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National Conf. on crystal growth, Huangshan, sep. 1991

The amplitude of the voltage across the capacitor is

$$V_C = \frac{n^2}{n^2 - 1} V \tag{5.9}$$

The TSC branch can be disconnected ("switched out") at any current zero by prior removal of the gate drive to the thyristor valve. At the current zero crossing, the capacitor voltage is at its peak value, $v_{C,i=0} = Vn^2/(n^2 - 1)$. The disconnected capacitor stays charged to this voltage and, consequently, the voltage across the non-conducting thyristor valve varies between zero and the peak-to-peak value of the applied ac voltage, as illustrated in Figure 5.13(b).

If the voltage across the disconnected capacitor remained unchanged, the TSC bank could be switched in again, without any transient, at the appropriate peak of the applied ac voltage, as illustrated for a positively and negatively charged capacitor in Figure 5.14(a) and (b), respectively. Normally, the capacitor bank is discharged after disconnection. Thus, the reconnection of the capacitor may have to be executed at some residual capacitor voltage between zero and $Vn^2/(n^2 - 1)$. This can be accomplished with the minimum possible transient disturbance if the thyristor valve is turned on at those instants at which the capacitor residual voltage and the applied ac voltage are equal, that is, when the voltage across the thyristor valve is zero. Figure 5.15(a) and (b) illustrate the switching transients obtained with a fully and a partially discharged capacitor. These transients are caused by the nonzero dv/dt at the instant of switching, which, without the series reactor, would result in an instantaneous current of $i_C = Cdv/dt$ in the capacitor. (This current represents the instantaneous value of the steady-

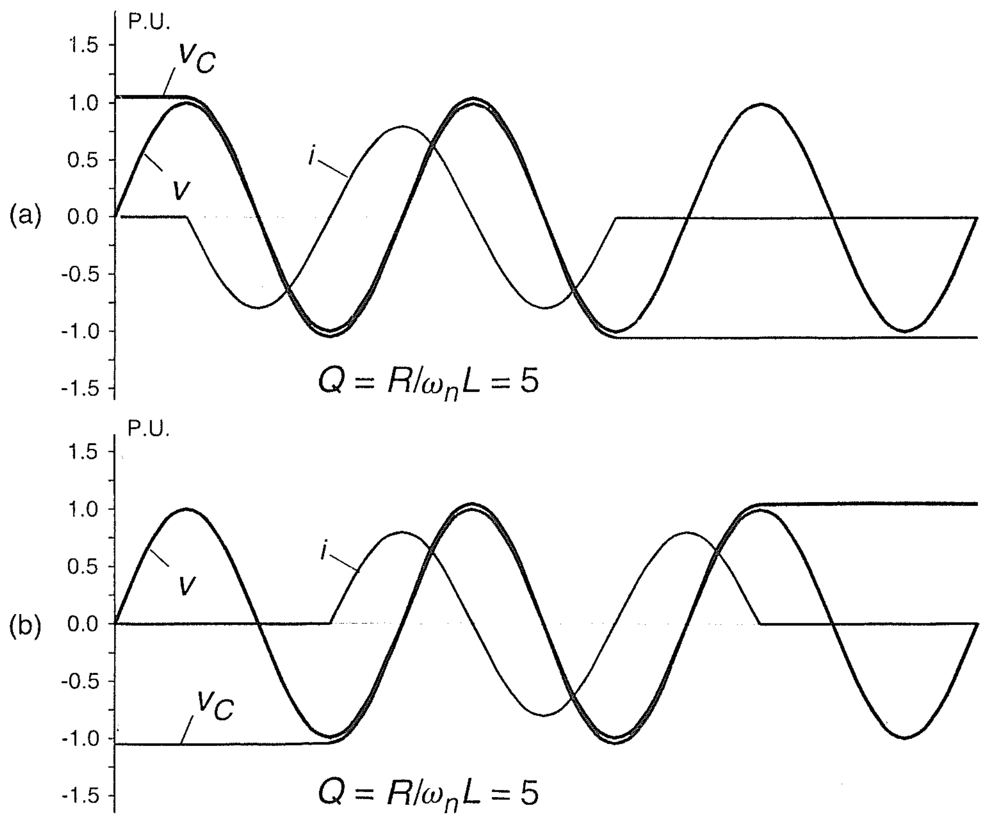

Figure 5.14 Waveforms illustrating transient-free switching by a thyristor-switched capacitor.