Experimental Observation of Thermal Self- Modulation in OPO

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Abstract

The thermal self-modulation has been observed experimentally via SHG in OPO. the threshold pump power for the thermal self- modulation is much smaller than that of the nonlinear self-pulsing. The thermal effect prevent from realizing the theoretical prediction for the self-pulsing.

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1 Introduction

In recent years the interest in the continuous optical parametric oscillators (OPO's) has been renewed because of their ability to generate nonclassical states of light efficiently[1,2]. The bright amplitude squeezed light have been produced from the single and double resonant OPO's through second-harmonic generation (SHG)[3,4]. Due to technical problem, especially thermal instibility, the double resonance system was not stable[4]. Therefor it is necessary to study the thermal effects in OPO's

In 1978 K.J.McNell et. al. predicted the self-pulsing behaviour in the intensity of the second harmonic mode for sufficient strong coherent input to the fundamental mode[5]. Plenty of theoretical papers in this subject has been published but so far there is no experimental result to be presented to our knowledge. We designed a ring OPO to realize self-pulsing experimental. Although a similar intensity modulation phenomenon between the second harmonic mode and the fundamental mode has been observed the oscillation period was totally different with that predicted by McNell et. al.. The theoretical analyses showed that the intensity modulation recorded by us derived from the thermal effect in the nonlinear crystal. We named it thermal self-modulation. The thermal self-modulation effect can be explained by means of the phase mismatching of SHG during the crystal temperature rising due to the absorption. Our experiment points out that the threshold of the thermal self-modulation is much lower than that of the self-pulsing giving in ref.[5] for the crystals with the large absorption to the second harmonic wave such as $LiNbO_3$. The thermal effect prevents from demonstrating experimentally to the nonlinear self-pulsing predictions. This might be the reason of that why the experimental observation has not been finished untill now. In this paper we shall present the experimental results of the thermal self-modulation and compare the threshold power of the thermal self-modulation with that of the nonlinear self- pulsing.

2 Experimental set-up and result

We designed a ring OPO cavity to prevent the laser source from being desturbed by the feedback light. The pump source is a frequency- stablized cw ring $Nd : YAG$ laser. The output power of $1.06\mu m$ wavelength up to $3W$ can be available. The experimental scheme is showen in Fig.1.

Fig.1

The OPO consists of four mirrors: M_1 and M_2 are the input and output couplers respectively with the curvature radiis of $20mm$ and $50mm$, M_3 and M_4 are the plane mirror with high reflectivty for both fundamental and second harmonic waves. The total length of ring cavity is $15cm$. The transmissivity of input coupler M_1 for the fundamental wave is $T_{1.06} = 4\%$ and it is highly reflective for harmonic wave. The output coupler M_2 is highly reflective for both waves. A $MgO : LiNbO_3$ of size $5 \times 5 \times 25cm$ was used as the nonlinear crystal for SHG. The crystal was placed on the common curvature centre of M_1 and M_2. A half wave plate HP placed front M_1 was used to align the polarization of the input pump light for optimum phase-matching. A beam splitter S following M_2 separated the leakage light from M_2 to two parts of $1.06\mu m$ and $0.53\mu m$ wavelengths. The detectors D_1 and D_2 respectively received the second harmonc wave ($0.53\mu m$) and the fundamental wave ($1.06\mu m$), then their power were analysed with the oscillascope (OS). The experimentally measured finesses of the OPO are 103 for $1.06\mu m$ wave and 136 for $0.53\mu m$ SH.

When the pump power were lower than $2.4W$ the increases of pump power results in the increase of SH power as usual. Once the pump power were over $2.4W$ the transmission curve of pump power presented the M-type (see Fig. 2).

Fig.2

The peak of SH wave was corresponding with the dip of M-type curve for the fundamental wave. Raising the pump power continuously when input power is over $2.7W$ the intensity modulation phenomena between the second harmonic mode and the fundamental mode were observed. The Fig. 3 (a) and (b) are the recorded experimental modulation curves at the pump power of $2.7W$ and $3W$. The period of modulation is about the order of millisecond. During recording this curves the cavity of OPO was locked in the pump frequency. By controlling the temperature of the crystal the cavity operated in near double resonant situation.

Fig.3

3 Discussion to the experimental results

The period of modulation (mS) in above experimental curve is 3 orders longer than that predicted by K.J.McNell et. al. (μS)[5]. Therefor they are totally different phenomena. Usually the thermal response time is at the order of millisecond. We consider that the observed intensity modulation derived from thermal effect. The absorptivity of the crystal used in our experiments for SH wave is $\alpha^{ab}_{0.53} = 0.012/cm$ which is much higher than that for the fundamental wave, so that the absorption for $1.06\mu m$ wave can be neglected, i.e. the crystal is heated up only through the absorption to SH wave. Due to that the refractive indexes n_o and n_e of crystal are the function of temperature, the heating up of crystal must result in the phase mis-match then the intensity of SH wave decreases and that of the fundamental wave increases. During the reduction of SH intensity the temperature of crystal drops down. When the temperature return to the phase matching point, the intensity of SH wave restores to the maximum. The temperature change between phase mis-matching and matching point results in the thermal self-modulation.

Based on experiment observation we calculated the critical temperature rising ΔT_{crit} and the phase mis-matching (Δk) for the thermal self-modulation. The nonlinear equation of motion for the slowly varying amplitudes α_1 and α_2 of the fundamental and the second harmonic waves in OPO are written as follows:

$$\dot{\alpha}_1 = -\gamma_1\alpha_1 + G_0\alpha_1\alpha_2 + E \tag{1}$$

$$\dot{\alpha}_2 = -\gamma_2\alpha_2 - \frac{1}{2}G_0\alpha_1^2 \tag{2}$$

where γ_1, γ_2 are the cavity damping rates for α_1 and α_2 modes. E is the pump parameter corresponding to the power of the coherent driving field. G_0 is the coupling coefficient at perfect phase matching. For our system $\gamma_1 = 7 \times 10^7$, $\gamma_2 = 4 \times 10^7$ and $G_0 = 57.15$. Substituting above parameters into eqs. (1) and (2) and taking $2.7W$ as the critical pump power we get the intracavity intensity of SH wave with which the thermal self- modulation starts. If the absorbed power of SH wave per unit volume is q the temperature rising at the radius r in the *Gaussian* beam due to the absorption is expressed as:

$$\Delta T_r = \frac{q\omega_0^2}{4k_c}\exp\left(\frac{-r^2}{\omega_0^2}\right) \tag{3}$$

k_c is the thermal conducttivity of crystal, ω_0 is the spot size of the SH beam in crystal. Integreting ΔT_r through the beam spot we obtain the average temperature rising $\overline{\Delta T}$:

$$\overline{\Delta T} = \frac{1}{\pi\omega_0^2}\int_0^{\omega_0} \Delta T_r 2\pi r \, \mathrm{d}r = 0.63\Delta T_0 \tag{4}$$

ΔT_0 is the temperature rising at the centre of beam ($r = 0$). The phase mis-matching (Δk) resulting from the temperature rising is equal to:

$$\Delta k = \frac{4\pi}{\lambda}\Delta T_r\left(\frac{\mathrm{d}n_\omega^e}{\mathrm{d}T} - \frac{\mathrm{d}n_{2\omega}^o}{\mathrm{d}T}\right) \tag{5}$$

here λ is the wavelength of fundamental wave, $\frac{\mathrm{d}n_\omega^o}{\mathrm{d}T}$ and $\frac{\mathrm{d}n_{2\omega}^e}{\mathrm{d}T}$ are the temperature coefficients of refractive indexes respectivly for the fundamental wave with ordinary polarization and the SH wave with extraordinary polarization. For $LiNbO_3$ crystal we have [8]

$$\frac{\mathrm{d}n_\omega^o}{\mathrm{d}T} - \frac{\mathrm{d}n_{2\omega}^e}{\mathrm{d}T} = -5.9 \times 10^{-5}$$

$$k_c = 5.6W/mK$$

In our experimental system $\omega_0 = 48\mu m$, we obtain the critical temperature rising:

$$\overline{\Delta T_{crit}} = 0.03\,^{\circ}C \tag{6}$$

and corresponding phase mis-matching:

$$\Delta k_{crit} = 21 \tag{7}$$

Obviously the thermal effect is very sensitive.

¿From ref.[5] the nonlinear self-pulsing read:

$$| E |^2 = \frac{(2\gamma_1 + \gamma_2)^2[2\gamma_2(\gamma_1 + \gamma_2)]}{G_0^2} \tag{8}$$

$$P_{th} = \frac{\hbar\omega\,\Delta t}{T_{1.06}} \mid E \mid^2 \tag{9}$$

Where Δt is the round trip time in the cavity. Using above given parameters we have:

$$P_{th} = 238W \tag{10}$$

Clearly P_{th} is much large than the critical pump power for the thermal self-modulation.

4 Conclusion

The phase matching condition for SHG in OPO may be disturbed by the thermal effect. When the absorption of crystal for SH wave is large the threshold pump power for the thermal self-modulation is much lower than that for the nonlinear self-pulsing predicted in ref.[5]. For realizing experimentally the nonlinear self-pulsing the crystal with quite low absorption for both fundamental and SH waves has to be chosen. Of course the crystal must also have high nonlinear coefficient. This might be the reseaon of that the nonlinear self-pulsing has not been observed experimentally so far.

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Figure Caption

Fig.1 The experimental set-up

Fig.2 The output curves of OPO at pump power $P = 2.4W$

Fig.3 The output curves of OPO at pump power (a) $P = 2.7W$, (b) $P = 3W$

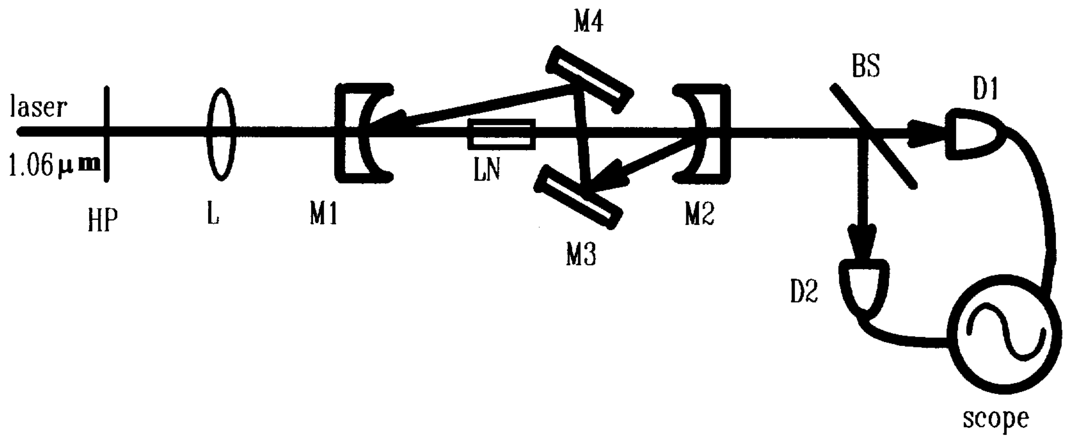
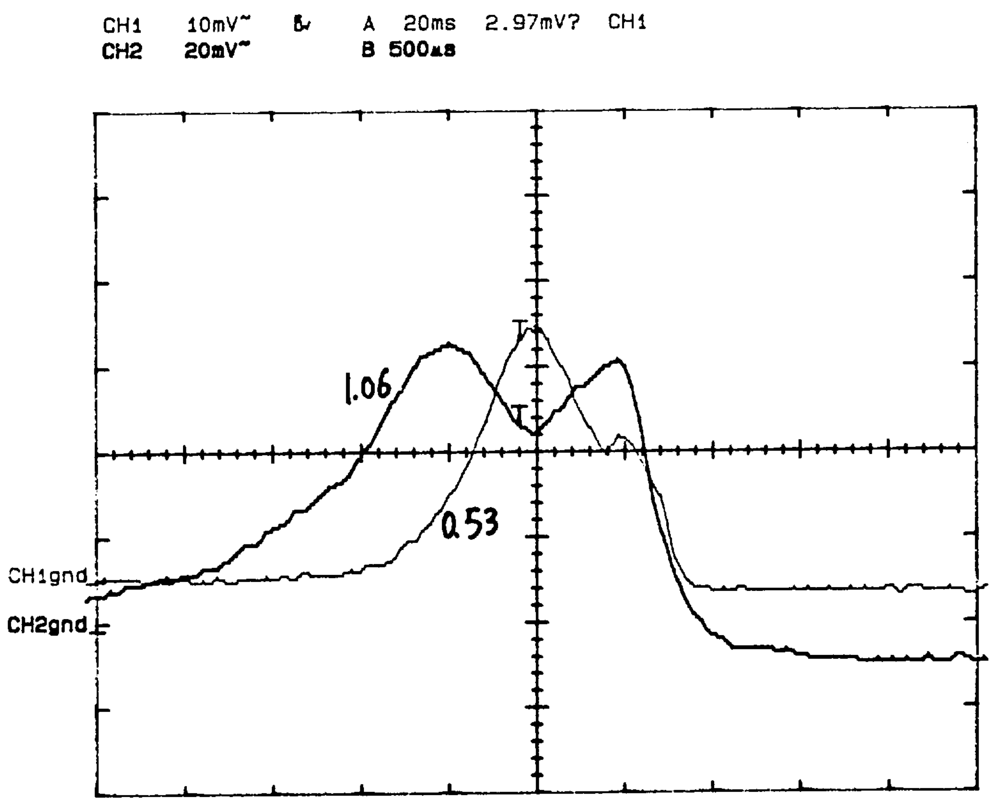


Fig. 1 Experimental Set-up



CH1 10mV~ A 20ms 2.97mV? CH1
CH2 20mV~ B 500µs
1.06
0.53
CH1gnd
CH2gnd

Fig. 2

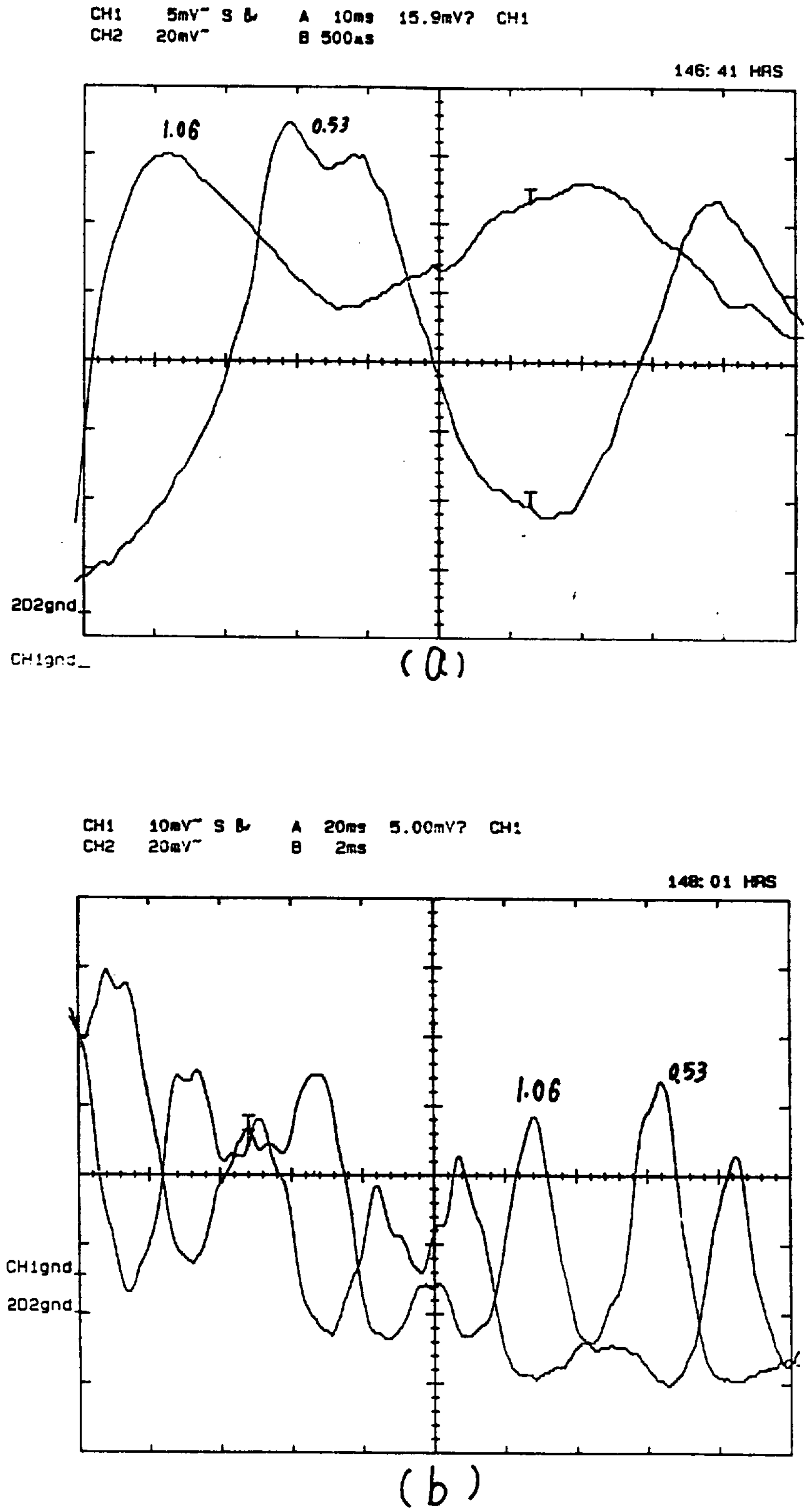

CH1 5mV~ S B A 10ms 15.9mV? CH1
CH2 20mV~ B 500µs
146:41 HRS
1.06
0.53
202gnd
CH1gnd
(a)
CH1 10mV~ S B A 20ms 5.00mV? CH1
CH2 20mV~ B 2ms
148:01 HRS
1.06
0.53
CH1gnd
202gnd
(b)

Fig. 3