The Effect of Thermal Effect of Magnesium Neodymium Double Doped Periodically Polarized Lithium Niobate on Self-Optical Parameter Oscillation

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Abstract. Based on the theory of thermal effect, the temperature rise, deformation and the deformation of periodically polarized region are simulated. The theory of nonlinear transformation, the effect of thermal effect on nonlinear effect is analyzed. Based on the oscillation theory of the laser resonator, the laser resonator was proposed to be constructed, and the influence of the laser resonator and the optical parametric oscillation was analyzed to describe the optical parametric oscillation process of Nd:MgO:PPLN crystal construction more accurately. The thermal effect of the original dynamic model of OPO in the inner cavity was modified to better reflect the actual situation of the compound self-optical parametric oscillator. The experimental study of the future self-optical parametric oscillator provided a design idea and laid a theoretical foundation for the subsequent experiments.

1. Introduction
Magnesium bismuth double doped Lithium Niobate (Nd:MgO:LN) crystals were introduced in the 1980s[1]. Early Nd:MgO:LN was mainly used for research on laser gain medium. In recent years, with the advancement of the crystal permanent polarization process, the Nd:MgO:LN crystal can be permanently polarized to Nd:MgO:PPLN[2], and the polarized crystal can be used as both a laser gain medium and a nonlinear frequency conversion medium. The structure of the original intracavity optical parametric oscillator was further simplified, and the independent fundamental frequency laser gain medium was reduced, so its role in the field of optical parametric oscillations is again mentioned. In 2012, the self-frequency conversion study based on Nd:MgO:PPLN crystal conducted by the Taiwan research group obtained the signal light laser output of 1525 nm[3]. This was one of the few research results of the crystal in the field of optical parametric oscillation, but the study did not analyze the detailed physical process of the self-optical parametric oscillator (S-OPO) constructed by Nd:MgO:PPLN crystal[4-7]. And there were no report on the optical parametric oscillators operating in mid-infrared range.

Based on the previous studies of the intracavity OPO dynamics model, this study focuses on the analysis of the thermal effects of Nd:MgO:PPLN crystals in optical parametric oscillators[8-12], and analyzes the effects of resonator and optical parametric oscillations. Then describe the optical parametric oscillation process of Nd:MgO:PPLN crystal construction more accurately.

2. Thermal effect analysis of Nd:MgO:PPLN crystal
In 1968, Oshman and Harris proposed the theoretical model of IOPO. In 1999, G. A. Turnbull et al. conducted a detailed analysis of the power characteristics of ICSR from the rate equation and the...
coupled wave equation\cite{13-14}. The main physical model of the construction was different from the physical model of the optical parametric oscillator as follows:

![Physical model of a s-OPO by a conventional internal cavity optical parametric oscillator and based on Nd:MgO:PPLN crystal.](image)

The dotted line in the above is the original classical intracavity singly-resonant continuous wave pumped optical parametric oscillator (CW-ICSRO) physical model. The laser resonator was separated from the nonlinear crystal. To perform pattern matching better, the laser cavity was separated from the parametric optical oscillation cavity. Combining the laser crystal and the nonlinear crystal in the above figure into one, the Nd:MgO:PPLN crystal acts as both a nonlinear crystal and a gain medium to form a physical model of S-OPO. This greatly simplifies the overall structure of the laser and naturally provides a good pattern matching of the fundamental and parametric lights. The following was a brief analysis of the physical process of S-OPO according to the ICSRO kinetic theory.

The thermal conductivity of the crystal is $K=0.0046 \, W/mm \cdot k$, and the pump spot is from the circular spot of $R=0.4mm$ to the elliptical spot. The long axis of the spot is 0.5mm, 1.5mm, and 2.5mm, the short axis is 0.4mm, and the crystal length is $l=40mm$. The absorption efficiency of the crystal for the pump light is $\eta = 0.175 \, mm^{-1}$.
The maximum crystal temperature is shown in the following table:

Table 1. Maximum temperature of different pump spot of Nd:MgO:PPLN crystals.

| Number | Spot a axis (mm) | Spot b axis(mm) | Crystal maximum temperature(K) |
|--------|------------------|-----------------|-------------------------------|
| a      | 0.4              | 0.4             | 561.58                        |
| b      | 0.5              | 0.4             | 533.14                        |
| c      | 1.5              | 0.4             | 399.88                        |
| d      | 2.5              | 0.4             | 358.79                        |

The maximum crystal temperature in the slab structure is 561.58 K at an external pumping rate of 100 W. Because the optical parametric oscillation of the PPLN crystal matches the temperature, the maximum temperature of the crystal continues to decrease as the area of the pump spot increases. However, the huge difference between this temperature difference and the previous intracavity OPO cannot be ignored.

We consider the change in refractive index caused by the temperature difference. According to the Nd:MgO:PPLN dispersion equation:\[15\]:

\[
n_e^2 = a_1 + b_1 f + \frac{a_3 + b_3 f}{\lambda^2 - (a_1 + b_3 f)^2} + \frac{a_4 + b_4 f}{\lambda^2 - a_5^2} - a_6 \lambda^2
\]

\[f = (T - 24.5)(T + 570.82)\]  

The simulation results in a change in the three-wave refractive index in the crystal as a function of the external pumping rate.

Figure 3. The relationship between the three-wave refractive index of Nd:MgO: PPLN crystal center and the external pump power.
Then according to the beam waist formula of the ABCD matrix in the laser cavity, the beam waist variation law of the center of the Nd:MgO:PPLN crystal is determined. The effect of the crystal's own thermal focal length is considered in the calculation process.

![Figure 4](image)

Figure 4. The relationship between the three beam waists at the center of Nd:MgO:PPLN crystal and the external pump power.

It can be seen that the three-beam waist radius of the center of the crystal changes significantly when injected with a small power pump. As the pump power increases, the beam waist radius tends to be flat.

The change of the waist radius and the change of the refractive index are brought into the dynamic model. Combined with the actual situation, we can obtain the variation law of the theoretical OPO idle frequency light output photon flow and down conversion efficiency.

![Figure 5](image)

Figure 5. Simulation curve of the traditional ICSR theory and the S-OPO idler light output power after considering the thermal effect.

A simulation curve of the theoretical output power of the S-OPO idler light after considering the thermal effect is shown in Figure 5. The main parameters selected are as follows:

- The stimulated emission cross section of Nd:MgO:PPLN crystal is $23.8 \times 10^{-24} \text{m}^2$.
- The upper energy level lifetime is 107μs.
- The signal light output mirror reflectance is 0.7.
- The cavity length is 60 mm.
- The crystal length is 50 mm.
- The fundamental frequency light loss is 0.04.
- The signal light oscillation loss is 0.04.

It can be found that the OPO threshold is increased when considering the thermal effect of the crystal. In the low pump power state, the idler light output power will be close to the conventional OPO theoretical value. However, as the pump power is gradually increased, the output power will be less than the theoretical output value without considering the crystal thermal effect. Next we analyze the relationship of the down conversion efficiency of S-OPO.
Figure 6. Simulation curve of the traditional ICSR theory and the conversion efficiency of the S-OPO self-optical parametric oscillator after considering the thermal effect.

It can be found from Figure 6. that in the self-optical parametric oscillator constructed with Nd:MgO:PPLN crystal as the core, the presence of thermal effect leads to an increase in the OPO threshold. The optimum down-conversion efficiency considering the thermal effect of the crystal will be delayed compared to the original theoretical value, and the maximum down-conversion efficiency is the same. As the effect of thermal effects increases, it will have a greater impact on the output power and down-conversion efficiency of idler light. In the large pump injection phase, the output power and down conversion efficiency of the optical parametric oscillator are greatly reduced. Therefore, it must be considered at the design stage of the resonant cavity to correct the effect of thermal effects on the self-optical parametric oscillator.

3. Conclusion:
The thermal effect of the Nd:MgO:PPLN crystal in the self-optical parametric oscillator was analyzed, and the thermal effect of the original intracavity OPO was corrected. That can better match the actual situation of the self-optical parametric oscillator. The influence of the existence of thermal effects on the self-optical parametric oscillator is analyzed by numerical simulation. The experimental research on the future self-lighted parametric oscillator provides a design idea and lays a theoretical foundation for subsequent research.

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