Performance evaluation of high power PPLN OPO influenced by cavity configurations and thermal effects

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***Abstract*—Numerical simulations for periodically poled lithium niobate (PPLN) optical parametric oscillators (OPO) with different cavity configurations are shown in this paper. The thermal effects of PPLN are investigated. The power variation caused by the mode matching in different cavity configurations and the thermal relaxation of the PPLN OPO are observed in the experiments. These results can be explained by the mode changing due to the thermal lens effect.**

Keywords- optical parametric oscillator; periodic poled lithium niobate; thermal effect; mode matching

I. INTRODUCTION

OPO is an important technique for frequency conversion, especially in infrared band. OPOs base on PPLN are one of the widely use technique in generation of high power near-infrared and mid- infrared. In practice, the configurations of the OPO and thermal effects could influence the conversion efficiency of the OPOs.

In this paper, we discuss the variation of the conversion efficiency and beam quality of PPLN OPOs in different cavity configurations, and investigate the thermal effects of the PPLN. Also, the experiment results of Nd:YVO_4 pumped PPLN OPOs are presented in this paper. The works shown here are all based on the near degenerate PPLN OPO, operating from 1064nm to 2128nm.

II. THEORYTICAL INVESTIGATION

A. Numerical Simulations for Several Resonators

To study the performance of PPLN OPOs in different cavity configurations, a numerical simulation method is employed. The analysis is performed by using the SNLO[1].

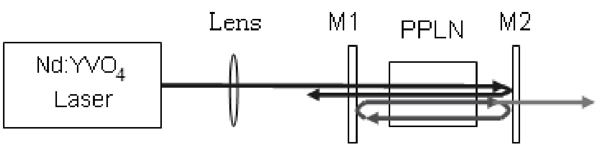

Figure 1. The schematic diagram of Nd:YVO4 laser pump PPLN OPO

The schematic diagram of 1μm laser pump PPLN OPO is shown in figure 1. One micron laser is focused in the center of the PPLN crystal by a convex lens with focal length of 300mm. The OPO is configured as a planar cavity .The input mirror M1, is a flat mirror with high transmission (HT) at 1064nm and high reflection (HR) at the parametric light wavelength of 2128nm. The output coupler (OC) mirror M2 is another flat mirror with transmission of 35% at 2128nm and HR at 1064nm. It means that the M2 reflects the pump laser back into the OPO, forming a double-pump pumping. The length of PPLN crystal is 20mm, and the effective nonlinear coefficient is ~17pV/m. The loss and walk-off effect of the PPLN is neglected in the simulation.

To study the performance of PPLN OPOs, the influence of the cavity with different cavity lengths is investigated. It is well known that short resonators could minimize the signal buildup time and achieve maximum output energy, but make the beam quality getting worse. Here, the cavity length is set at 58mm, 70mm, 80mm, respectively. The curves of the output energy and the beam quality are calculated and shown in figure 2.

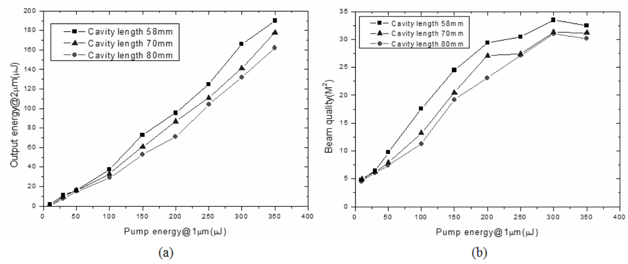

Figure 2. Calculated output energy and beam quality for different cavity lengths.(a)The output power. (b)The beam quality.

The results agree with the above description. Both of the cases obtain a low threshold and high conversion efficiency (maximum 54%) due to the large nonlinear coefficient of PPLN. In figure 2(a), there is a quasi-linear relation between the output energy and the pump energy. In figure 2(b), the beam quality becomes stable in high pump energy.

In the following, we investigate how the position of the PPLN in the resonator affects the output energy. Two OPOs

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with lengths of 70mm and 80mm are considered here. In the 70mm length resonator, the PPLN is located 19mm, 25mm and 31mm apart from the OC mirror. And the PPLN is placed 19mm, 30mm and 41mm apart from the OC mirror in the 80mm length cavity. The pumped laser is kept focusing in the center of the PPLN in those cases. Figure 3 shows the calculated output energy as functions of the pump energy for the two cavities.

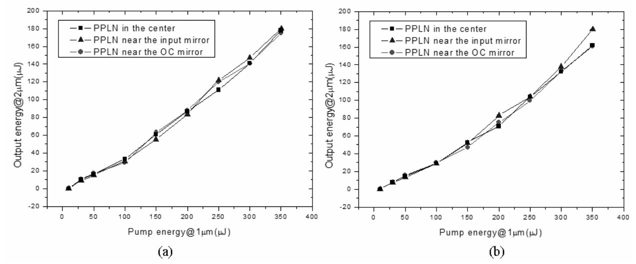

Figure 3. Calculated output energy for different position of the PPLN in the resonator. (a)The length of the OPO is 70mm. (b)The length of the OPO is 80mm.

It is interesting to find that the location of PPLN do not affect the output energy remarkably in the resonators which have the same cavity length. During the calculations, the pump laser is always focusing in the same location of the PPLN and the width of the 2128nm Gaussian beam is set to the same value. Additionally, the confocal parameter of the pump laser is larger than the length of the resonator. Those setups lead to the similar conditions of mode matching and bring the result that the output energy is insensitive to the location of PPLN.

B. Investigate the Thermal Effect of PPLN Crystal

In the above calculations, the thermal effects of the PPLN are neglected. However, the performance of the PPLN OPO will be affected by the thermal effects in practice. When a laser pumps the PPLN crystal, a refractive index gradient will be produced in the material. The optical behaviour of the crystal is like that of an optical lens. This phenomenon can influence the modes of the parameter beam in the OPO, and further affect the mode matching between the pump beam and the parameter beam.

As we know, the OPO gets good performance while the beam waists of the pump beam and the parameter beams satisfy the following condition[2][3]

$$\frac{1}{\omega_{\text{pump}}^2}=\frac{1}{\omega_{\text{signal}}^2}+\frac{1}{\omega_{\text{idler}}^2}. \tag{1}$$

In our work, the OPOs are operating near degeneration, so equation (1) becomes

$$\frac{\omega_{para}}{\omega_{\text{pump}}}=\sqrt{2}. \tag{2}$$

Where ω_{pump} is the waist of the pump beam inside the PPLN crystal , ω_{para} is the waist of parameter beam inside the PPLN crystal. While the beam waists satisfy equation (2), the efficiency of OPO will be maximized. However, the beam waists do not always match equation (2) exactly. So if the proportion between ω_{para} and ω_{pump} get farther to square root of two, then the performance of PPLN OPO will become worse. Suppose that the parameter beam propagated in resonator is the fundamental mode beam with beam width of ω_{para}. The value of $\omega_{\text{para}}/\omega_{\text{pump}}$ will affect the efficiency of OPOs.

The transfer matrix method can be used here to solve the fundamental mode of OPOs. The transfer matrix to express the thermal features inside the PPLN can be written by[4]

$$M(z)=\begin{cases}\begin{pmatrix}\cos\left(z\sqrt{\kappa}\right) & \dfrac{\sin\left(z\sqrt{\kappa}\right)}{n_{\text{ppln}}\sqrt{\kappa}}\\ -\sqrt{\kappa}\sin\left(z\sqrt{\kappa}\right) & \dfrac{\cos\left(z\sqrt{\kappa}\right)}{n_{\text{ppln}}}\end{pmatrix} & \text{if } z<l_{\text{ppln}}\\ \begin{pmatrix}\cos\left(z\sqrt{\kappa}\right) & \dfrac{\sin\left(z\sqrt{\kappa}\right)}{n_{\text{ppln}}\sqrt{\kappa}}\\ -n_{\text{ppln}}\sqrt{\kappa}\sin\left(z\sqrt{\kappa}\right) & \cos\left(z\sqrt{\kappa}\right)\end{pmatrix} & \text{if } z=l_{\text{ppln}}.\end{cases} \tag{3}$$

Where l_{ppln} and n_{ppln} are the length and refractive index of the PPLN crystal. For convenience, only the temperature induced refractive-index gradient is considered here, while the thermal strain and the surface distortion are ignored. So the κ can be expressed by

$$\kappa=\frac{P_{abs}}{\pi\omega_0^2 l_{\text{ppln}}K}\left(\frac{1}{2n_{\text{ppln}}}\frac{\mathrm{d}n}{\mathrm{d}T}\right). \tag{4}$$

Where K is the thermal conductivity, ω_0 is the beam waist inside the crystal, P_{abs} is the absorbed pump power inside the crystal, $\mathrm{d}n/\mathrm{d}T$ is the temperature coefficient of the refractive index.

The focal length of the thermal lens of PPLN can be calculated by[5]

$$f_{\text{ppln}}=\frac{K\pi\omega_0}{P_{abs}}\left(\frac{1}{2}\frac{\mathrm{d}n}{\mathrm{d}T}\right)^{-1}. \tag{5}$$

The magnitude of the focal lengths calculated by equation (3) is close to the experiment data in [6]. The parameters are used with follow value:

$$K=4.6\mathrm{Wm^{-1}{}^{\circ}C^{-1}},\ dn/dT=3.88\times10^{-5}{}^{\circ}\mathrm{C}^{-1},\ l_{\text{ppln}}=20\mathrm{mm}.$$

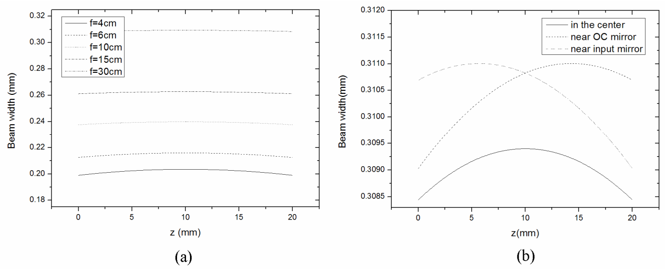

Figure 4. Width distribution of the parameter beam inside the PPLN crystal. (a) different thermal focal lengths in the same cavity. (b) different cavity configurations with the same focus

By using equation (3), the fundamental mode of the parameter beam in OPO can be calculated; also the width of the parameter beam inside the PPLN crystal can be obtained. For different thermal focal lengths in the same cavity or different cavity configurations with the same focus, the modes of parameter beam are different. In the first case, the width of parameter beam increase with the increasing of thermal focal length as shown in figure 4(a). In the latter case, shown in figure 4(b), when the PPLN placed closer to the OPO mirror from the center, the beam width will enlarge slightly.

III. EXPERIMENT AND DISCUSSION

The experiment setup is shown in figure 1. A commercial $Nd:YVO_4$ laser is used to pump the PPLN OPO. This is a laser diode pumped $Nd:YVO_4$ pulse laser, operated with a repetition frequency at 20kHz and the maximal output power is 6.7W. The pulse width is about 10ns and the beam quality factor (M2) is about 1.2. The setup of the PPLN OPO is the same as the description in section IA. A 3×3×20mm PPLN with poled period of 32μm is used in our experiment.

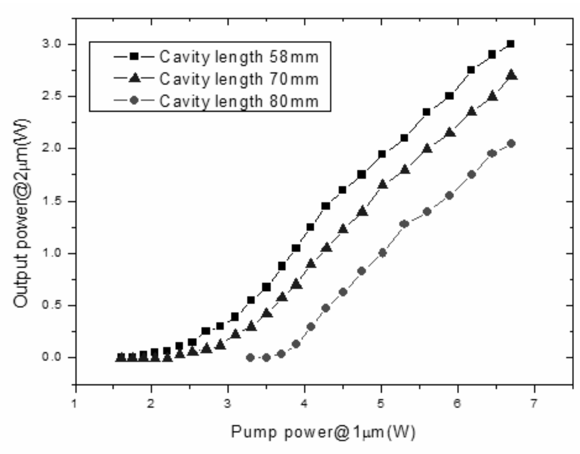

Figure 5. Performance of OPOs with different cavity length

First, the experiments with different lengths of OPO are performed. Figure 5 shows the results. We can see that the output power increases in shorter resonator, agree with the simulation in section IA. However, the thresholds are different here. In the simulation, the loss of the diffraction and the absorption of the crystal are neglected. In practice, longer resonator has higher diffraction loss, so the 58mm length cavity has the lowest threshold, while the 80mm one has the highest threshold in the experiment. An output power of 3W at 2128nm is obtained in the 58mm length PPLN OPO, when pumping by a 6.7W laser at 1064nm. The slope efficiency is about 65% in those cases.

Next, the location of the PPLN in the cavity is change from the place which near the input mirror to that near the OC mirror in 70mm length cavity and 80mm length cavity, respectively. We keep the pump beam focusing in the middle of the PPLN during the experiment and only shift the cavity by moving the two mirrors. The experiment results are shown in figure 6. The experiment results here are quite different from the calculations that shown in figure 3. The output power increases when placing the PPLN crystal near the OPO mirror. The reason may be expressed as follow. As seen in section IB, due to the short focus of PPLN, ω_{para} is very small so that the proportion between ω_{para} and ω_{pump} will be less than square root of two. The width of the pump beam inside the crystal does not change much during the process of the experiment. Otherwise, figure 4(b) tells us that placing the PPLN near the OPO mirror leads to enlargement of ω_{para} inside the crystal. So the value of $\omega_{para}/\omega_{pump}$ will become closer to square root of two when putting the PPLN in either end of the cavity, rather than that in the center. It means that shifting the crystal away from the center will get better performance here, while the conversion efficiency will be minimized with locating the PPLN in the center of the resonator.

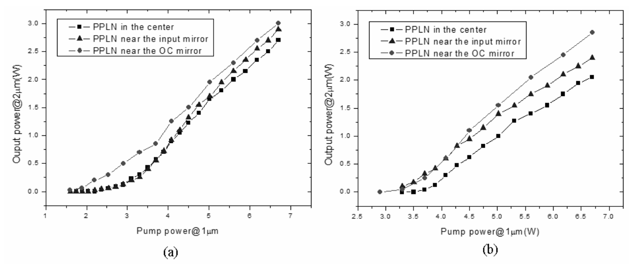

Figure 6. Experiment results for different position of the PPLN in the resonator. (a)The length of the OPO is 70mm. (b)The length of the OPO is 80mm.

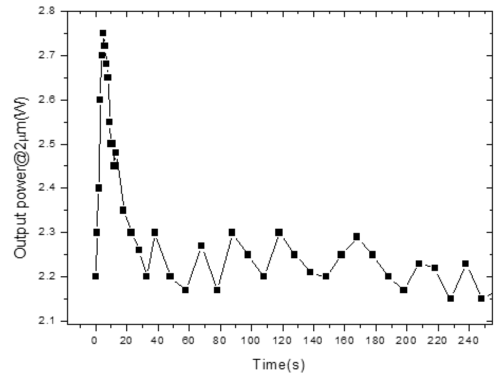

Figure 7. Thermal relaxation of the OPO

The thermal relaxation of the OPO is also observed in the experiment. The relaxation process is shown in figure 7. This phenomenon can be explained by the process of mode matching. Before the pump beam enters the PPLN, the temperature distribution of the crystal is uniform. When begin pumping, the distribution of the temperature becomes similar to the profile of the pump beam. Then the refractive index gradient also gradually turns to a stable stage that also has a similar profile of the pump beam. In the relaxation process, ω_{para} decreases from infinity to a minimum with the reducing of the thermal focal length of the PPLN crystal. As a result , the output power will grow at first with the $\omega_{para}/\omega_{pump}$ larger than square root of two, then reaches the maximum when $\omega_{para}/\omega_{pump}$ equal to square root of two, and at last decay to stabilization. This process results in the output power variation that is illustrated in figure 7. From figure 7, we achieved that the rise time is about 10 seconds and the decay time is about 20 seconds. It means that the thermal lens decreases fast at first from infinity, and then decays a bit slowly to the stable point. Also, the peak power is about 25% higher than that in stable stage.

IV. CONCLUSION

PPLN OPO simulations for different cavity configurations without thermal effects are firstly shown here, and the results show that shorter resonator have higher power. However, it will be quite different when the thermal effects are considered. The mode inside the resonator will be changed due to the variation of thermal lens of the crystal, and the level of the mode matching will alter results in the shifting of conversion efficiency. This thermally induced power variation phenomenon in different cavity configurations are observed in the experiments. And the changing process of the output power agrees well with our analysis. Furthermore, the thermal relaxation of PPLN crystal also appears in the experiment in the initial several seconds and it is explained by the mode matching and the mode changing that is described in section IB. In conclusion, according to the mode matching condition, the conversion efficiency of the OPO can be optimized by managing the mode of resonator when considering thermal effects.

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