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Research on the mechanism of picosecond pulse synchronously pumped mid-infrared MgO: PPLN Optical Parametric Amplification

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Abstract: In this paper, the mechanism of synchronously pumped MgO:PPLN picosecond optical parametric amplification is studied in depth, and it is concluded that with the change of the crystal length, the three-wave coupling process changes periodically. It is further obtained that as the intensity of the injected seed signal light and pump light increases, the optimal coupling length of the MgO: PPLN crystal gradually becomes smaller. Based on the OPA mechanism research, the factors affecting the gain and linewidth broadening of the optical parametric amplification process are analyzed, and it is concluded that the center gain of the MgO:PPLN crystal increases with the increase of the pump light intensity, the length of the crystal, and the decrease of the wavelength of the idler light. The linewidth of idler light gradually decreases with the increase of the wavelength, so it is easier to obtain a narrow linewidth when operating in the long wave range. In addition, it can be seen that with the increase of the linewidth of the injected seed signal, the larger the linewidth of the idler is. This study provides a theoretical basis for the design and experimental study of the synchronously pumped MgO: PPLN picosecond optical parametric amplification laser system.

1. Introduction

Synchronous pumped optical parametric oscillator (OPO) and optical parametric amplification (OPA) are important methods to produce tunable ultrashort laser pulses, which can reach the spectral range that traditional mode-locked lasers cannot cover. Using synchronous pumping to generate picosecond and femtosecond pulses with a wide tuning range of 3-5μm mid-infrared band has a wide application prospect in the fields of national defense, scientific research and civil use, such as photoelectric countermeasure, atmospheric monitoring, terahertz field generation, free space optical communication, laser medical treatment [1-4]. Compared with femtosecond OPO, picosecond optical parametric oscillator can not only achieve a balance between short pulse width and narrow spectral linewidth, but also has the potential to achieve high average power output, so it has advantages in many applications.

The development of the synchronously pumped mid-infrared parametric conversion laser system mainly depends on two factors: a high-quality nonlinear frequency conversion crystal and a laser pump source with excellent performance. In recent years, quasi phase matching technology has developed rapidly. Periodic polarization doped MgO lithium niobate crystal (MgO:PPLN) has become the most commonly used mid infrared quasi phase matching crystal due to its excellent properties such as large nonlinear coefficient and high damage threshold. There have been many reports of OPO based on MgO: PPLN crystals [5-6]. On the other hand, its development also depends on the high power mode-locked laser pumping source. Most of the previous picosecond OPO and OPA systems used mode-locked Ti: sapphire laser and other bulk solid-state lasers as pumping sources [7-8]. However, these methods generally have the disadvantages of large volume, complex structure and poor stability. Fiber laser has the advantages of compact structure and high efficiency, and can maintain high beam quality while high power output. Using fiber laser as a pumping source will greatly improve the efficiency and output stability of the laser system [9-10]. MgO: PPLN optical parametric amplifier is based on the optical parametric oscillator. Because of the relatively low optical damage threshold of the mid infrared film system, and the inevitable linewidth broadening of the optical parametric oscillator according to the literature research, in order to obtain high-energy parametric light output under the premise of ensuring the stable operation of the laser system, the technical system of small energy stable output optical parametric oscillator seed light injection cascade pump optical parametric amplifier is usually used. Therefore, while the parametric light energy is effectively amplified, it is not limited by the damage threshold of the resonant cavity mirror, and the output line width of the parametric light is effectively compressed.

In this paper, the mechanism of synchronously pumped MgO: PPLN picosecond optical parametric amplification will be studied in depth, and on this basis, the factors affecting the gain and linewidth broadening of the optical parametric amplification process will be analyzed in depth. The results provide a theoretical basis for the realization of the synchronously pumped MgO: PPLN picosecond optical parametric amplification laser system.

2. The mechanism of OPA

Although the optical parametric amplifier does not have the resonant cavity mirrors of the optical parametric oscillator, the parametric light will not form the oscillation, but its essence is also achieved by the parametric conversion, which also satisfies the conversion process of three-wave coupling equation ω3=ω1+ω2. The essence is that when the pump light ω3 is incident, it is accompanied by a weak signal light ω1 with a certain intensity. Note that the weak signal here is not the noise signal when the optical parameter oscillates. In fact, it is generally of the same magnitude as the pump light. Thus, two beams are converted into three-wave coupling, and the amplification of parametric light is realized in the amplification crystal. Compared with the optical parametric oscillator, the conversion efficiency of the optical parametric amplifier is lower, but its stability is better. If the operating conditions of the laser system are effectively controlled, the multi-stage amplification of high energy parametric optical output can be realized.

As the three-wave coupling equation is the same as the optical parametric oscillator, its normalized coupling wave equation is:

$$\begin{cases} \dfrac{\partial u_1}{\partial \xi} = -u_2 u_3 \sin\theta \\ \dfrac{\partial u_2}{\partial \xi} = -u_1 u_3 \sin\theta \\ \dfrac{\partial u_3}{\partial \xi} = u_1 u_2 \sin\theta \\ \cos\theta = (\Gamma - \dfrac{1}{2}\Delta S u_3^2)\dfrac{1}{u_1 u_2 u_3} \end{cases} \tag{1}$$

Where, $\Gamma = u_1(0)u_2(0)u_3(0)\cos\theta(0) + \frac{1}{2}\Delta S u_3^2(0)$ is the normalized photon current density, ξ is the normalized length, and ΔS is a constant independent of z. The general solution of the coupled wave equation is obtained:

$$\begin{cases} A_1(z) = (B_{11}e^{gz} + B_{12}e^{-gz})e^{\frac{i\Delta k}{2}z} \\ A_2(z) = (B_{21}e^{gz} + B_{22}e^{-gz})e^{\frac{i\Delta k}{2}z} \end{cases} \tag{2}$$

Where, B_{11}, B_{12}, B_{21} and B_{22} are undetermined coefficients, which can be determined by boundary conditions. The boundary condition of OPA is not the same as that of OPO. Because there is the seed light of signal light injected in the initial state, the noise light intensity of this idler light is much smaller and can be ignored. Therefore, the boundary condition of optical parametric amplification is given as follows:

$$\begin{aligned} &A_1(z)\big|_{z=0} = A_1(0) \\ &A_2(z)\big|_{z=0} = 0 \\ &\left.\frac{\partial A_1(z)}{\partial z}\right|_{z=0} = i\sigma_1 A_2^*(0) A_3(0) \end{aligned} \tag{3}$$

The small signal approximate solution of the optical parametric amplification process can be obtained:

$$\begin{cases} A_1(z) = A_1(0) e^{i\frac{\Delta k}{2}z}\left(\cosh gz - i\dfrac{\Delta k}{2g}\sinh gz\right) \\ A_2(z) = i\dfrac{1}{g}\sigma_2 A_1^*(0) A_3(0) e^{i\frac{\Delta k}{2}z}\sinh gz \end{cases} \tag{4}$$

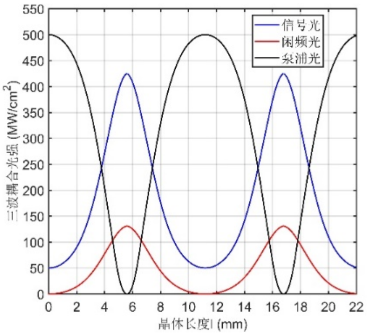
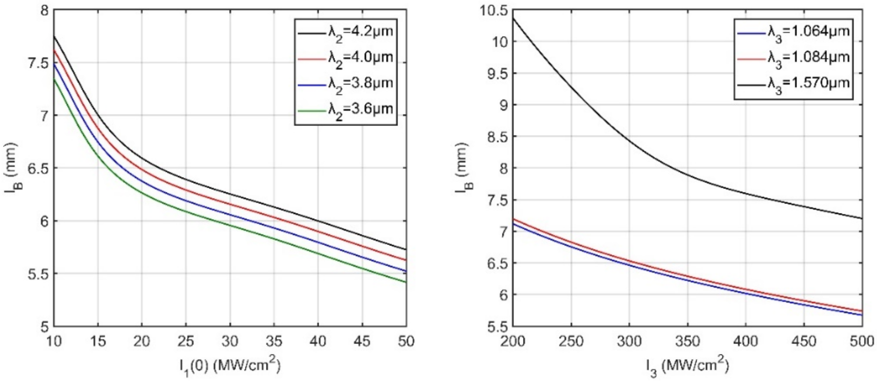


Figure 1 The curve of three-wave light intensity changing with the length of MgO: PPLN crystal

In the case of phase matching $\Delta k=0$, the parameters of optical parametric oscillation are adopted for the three-wave wavelength. The pump light, signal light and idler light are $\lambda_3=1.064\mu m$, $\lambda_1=1.34\mu m$, and $\lambda_2=4.1\mu m$, respectively. The initial pump light intensity is $I_3(0)=50MW/cm^2$, and the initial signal light intensity of the injected seed is $I_1(0)=5MW/cm^2$. Therefore, the relationship between the three-wave light intensity and the length of MgO: PPLN crystal can be obtained, as shown in Figure 1. It can be seen from the figure that with the change of crystal length, the three-wave coupling process changes periodically. Therefore, in order to obtain the best conversion efficiency output of idler light, the best crystal length needs to be selected.



(a) the initial signal light intensity (b) the initial pump light intensity

Figure 2 The curve of the effect of parametric light intensity on optical parametric amplification process on the optimal length of MgO: PPLN crystal

Therefore, the influence of the initial signal light intensity and the initial pump light intensity on the optical parametric amplification process on the optimal length of the MgO: PPLN crystal can be further obtained, as shown in Figure 2. It can be seen from the figure that with the increase of the intensity of the injected seed signal light and the pump light, the optimal coupling length of the crystal gradually decreases. Therefore, when choosing a certain pump power, we should choose a smaller signal light injection, or use multiple MgO: PPLN crystals to realize multi-stage OPA amplification.

3. The analysis of OPA output characteristics

Set the length of the MgO: PPLN crystal as *l*, then the signal optical complex amplitude of the optical parametric amplification output from the small signal solution (4) is:

$$A_1(z) = A_1(0)e^{i\frac{\Delta k}{2}l}\left(\cosh gl - i\frac{\Delta k}{2g}\sinh gl\right) \tag{5}$$

The pump light used here is approximated by a Gaussian beam, so there are $g=\sqrt{\Gamma_0^2-(\Delta k/2)^2}$ and $\Gamma_0=\sqrt{\sigma_1\sigma_2 A_3(0)A_3^*(0)}$ in the above formula. Thus, the signal light intensity output by the optical parametric amplifier is obtained:

$$I_1(l) = \frac{1}{2}n_1\varepsilon_0 c A_1(l)A_1^*(l) = I_1(0)\left[1+(\frac{\Gamma_0^2}{g})^2\sinh^2 gl\right] \tag{6}$$

The gain of the optical parametric amplifier can be obtained as follows:

$$G = \frac{I_1(l)-I_1(0)}{I_1(0)} = (\frac{\Gamma_0^2}{g})^2\sinh^2 gl = \Gamma_0^2 l^2\left\{\frac{\sinh\left[\left(\Gamma_0^2-(\frac{\Delta k}{2})^2\right)^{1/2} l\right]}{\left(\Gamma_0^2-(\frac{\Delta k}{2})^2\right)^{1/2} l}\right\}^2 \tag{7}$$

Under the Gaussian beam approximation, $(\Gamma_G l)^2 = g_1 g_2(\Gamma_0 l)^2$,the gain of the optical parametric amplifier pumped by the Gaussian beam is:

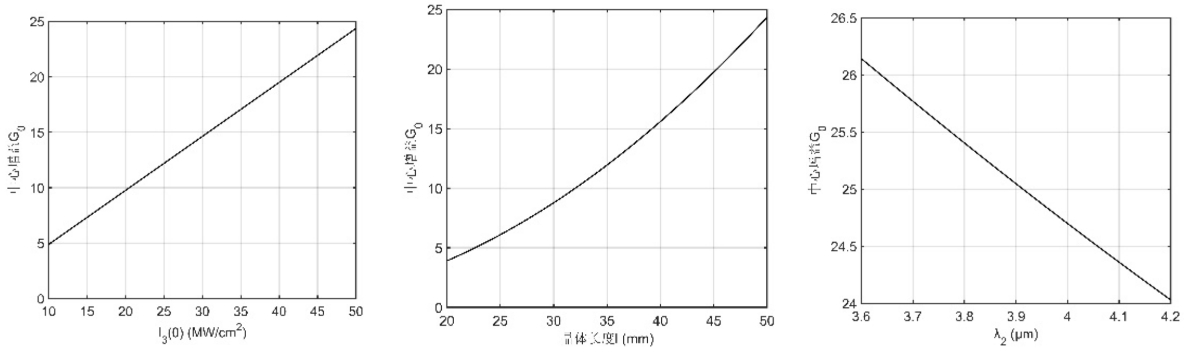
$$G = 4\frac{w_3^2}{W_{123}^2}\Gamma_0^2 l^2\left\{\frac{\sinh\left[\left(4\frac{w_3^2}{W_{123}^2}\Gamma_0^2 l^2-(\frac{\Delta kl}{2})^2\right)^{1/2}\right]}{\left(4\frac{w_3^2}{W_{123}^2}\Gamma_0^2 l^2-(\frac{\Delta kl}{2})^2\right)^{1/2}}\right\}^2 \tag{8}$$

Where, $W_{123} = (w_1^2 w_3^2 + w_2^2 w_3^2 + w_1^2 w_2^2)/(w_1 w_2 w_3)$ is the spatial coupling coefficient, w_1, w_2, and w_3 are the three-wave spot radius. It can be seen from the formula that the gain value is the largest when Δk=0, because it is in the ideal phase matching situation at this time, that is, the center of the optical axis does not move away, so the center gain is defined at this time:

$$G_0 = \sinh^2(2\frac{w_3}{W_{123}}\Gamma_0 l) \tag{9}$$

If the pump light is very weak, or the crystal is very short (the gain length is very short), it can be considered that $\Gamma_0 l \ll 1$ at this time, and the above equation becomes approximately:

$$G_0 \approx 4\frac{w_3^2}{W_{123}^2}\Gamma_0^2 l^2 = \frac{w_3^2}{W_{123}^2}\frac{2\mu_0\omega_1\omega_2\chi_{eff}^2 l^2}{cn_1n_2n_3}I_3(0) \tag{10}$$



(a) The pump light intensity (b) The crystal length (c) parametric wavelength

Figure 3 The center gain curve of MgO: PPLN optical parametric amplification at different parameters.

It can be seen from the above formula that the center gain increases with the increase of pump intensity and crystal length. In addition, the center gain increases with the increase of the product of $\omega_1\omega_2$, that is, the closer to the degeneracy point, the greater the center gain. This gives the center gain curve of MgO: PPLN optical parametric amplification at different pump light intensities, crystal lengths, and parametric wavelengths, as shown in Figure 3. It can be seen that the center gain increases with the increase of pump light intensity and crystal length, and decreases with the increase of idler wavelength. Therefore, in the case of selecting pump injection power and the operating wavelength of the idler light, it is necessary to combine the optimal crystal length and the central gain strength of the crystal to consider the selection comprehensively the best length of MgO: PPLN crystal.

In general, the seed signal light introduced during the optical parametric amplification process has a relatively small divergence angle. When the optical parametric amplification crystal is injected, it will usually be shaped by the coupling lens group to achieve the mode matching with the pump light. Therefore, due to the phase mismatch caused by the divergence angle of the signal light, the resulting output parameter light broadening can be ignored. However, although the seed signal light can be effectively compressed by oscillating the optical parameters and its linewidth is controlled, there is still a certain linewidth. Therefore, under the pump light injection, it will lead to the parametric light output satisfying different phase matching conditions, resulting in the broadening of the output parametric light linewidth. For a fixed wavelength mid-infrared idler light in MgO: PPLN optical parametric amplification, the phase mismatch mainly comes from the mismatch of pump light and seed signal light, which are:

$$\Delta k = \Delta k_3 - \Delta k_1 = \frac{dk_3}{d\tilde{\nu}_3}\Delta\tilde{\nu}_3 - \frac{dk_1}{d\tilde{\nu}_1}\Delta\tilde{\nu}_1 \tag{11}$$

Where, $d\tilde{\nu}_3 = d\tilde{\nu}_1$, it can be obtained that under the strong pump light of Gaussian pulse, the width of the idler light caused by the seed signal light linewidth is:

$$\Delta\tilde{\nu} = 0.3\frac{d\tilde{\nu}}{dk} = 0.3\left(\frac{n_{eff_3} - n_{eff_1}}{n_{eff_1} - n_{eff_2}}\right)\Delta\tilde{\nu}_1 \tag{12}$$

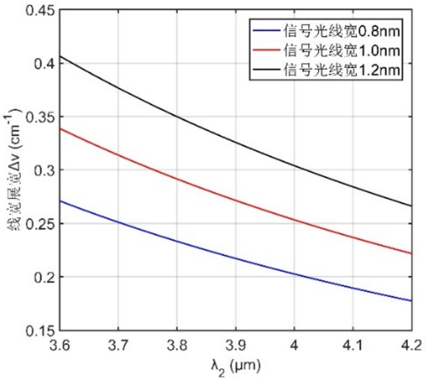


Figure 4 The curve of the idler light linewidth caused by the light width of the injected seed signal.

As a result, the curve of the idler light linewidth caused by the light width of the injected seed signal is given, as shown in Figure 4. It can be seen from the figure that as the wavelength of the obtained idler light increases, its linewidth becomes smaller and smaller, so it is easier to obtain a narrow linewidth when operating in the long wave range. In addition, it can be seen that with the increase of the linewidth of the injected seed signal, the more serious the linewidth of the idler is, so it is necessary to further control and optimize the light output linewidth of the signal in the design of the previous stage signal source.

4. Conclusion

In this paper, the mechanism of synchronously pumped MgO:PPLN picosecond optical parametric amplification is studied in depth, and it is concluded that with the change of the crystal length, the three-wave coupling process changes periodically. In order to obtain the best output conversion efficiency of idler light, it is necessary to select the best crystal length. Therefore, the effects of the initial signal light intensity and the initial pump light intensity on the optimal length of the MgO: PPLN optical parametric amplification process are obtained. It is concluded that the optimal coupling length of the crystal decreases with the increase of the intensity of the injected seed signal light and pump light. Therefore, when choosing a certain pump power, we should choose a smaller signal light injection, or use multiple MgO: PPLN crystals to realize multi-stage OPA amplification. Based on the study of OPA mechanism, the factors that affect the gain and linewidth broadening in the process of optical parametric amplification are analyzed. It is concluded that the central gain of MgO: PPLN crystal increases with the increase of pump intensity, crystal length and the decrease of idle wavelength. Therefore, in the case of selecting pump injection power and the operating wavelength of the idler light, it is necessary to combine the optimal crystal length and the central gain strength of the crystal to consider the selection comprehensively the best length of MgO: PPLN crystal. The linewidth of idler light gradually decreases with the increase of its operating wavelength, so it is easier to obtain a narrow linewidth when operating in the long wave range. In addition, it can be seen that with the increase of the linewidth of the injected seed signal, the more serious the linewidth of the idle frequency is. Therefore, it is necessary to further control and optimize the light output linewidth of the signal in the design of the previous stage signal source. In general, the above analysis results will provide a theoretical basis for the design and experimental research of synchronously pumped MgO: PPLN picosecond optical parametric amplification laser system.

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