Optical parametric oscillator based on electro-optically polarization mode conversion

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Abstract. The back conversion of optical parametric oscillator seriously restricts its application in spectral analysis, optical holography, lidar and so on. The optical parametric amplifier output energy is simulated theoretically, and it is confirmed that the back conversion can be compensated by reducing the input energy of parametric light. An optical parametric oscillator with electro-optically polarization mode converter in the resonant is proposed to change the polarization state of the parametric light and adjust the proportion involved in the oscillation. The polarization mode conversion of MgO:PPLN crystal is analyzed theoretically. The experiment of energy regulatory structure is carried out. When the applied voltage of electro-optically polarization mode converter is 157 V/mm, the maximum output power of 1.47 μm and 3.84 μm are 4.4 W and 3.7 W, with a ratio of 1.2. It is confirmed that such structure can suppress back conversion and adjust the output ratio.

1. Introduction

The nonlinear crystal in the optical parametric oscillator (OPO) can convert one pump photon into two parametric photons, in which a wide range and tunable laser output is obtained [1-7]. The OPO is widely used in the fields of spectral analysis, optical holography, laser radar and so on [8-10].

The back conversion always exists in the optical parametric oscillation, which leads to the efficiency reduction, the beam quality deterioration and the spectrum broadening [11-12]. There are several methods of back conversion compensation. A class of optical parametric oscillator reduces back conversion losses by removing idler photons from the active region of the OPO [13]. A non-collinear phase-matched OPO with a TPPLN crystal provides an optimized spatial quality for both the signal and the idler beam, which shows a substantial improvement in both the beam quality and the conversion efficiency [14]. The signal light reflectivity of output mirror affects the ratio of signal light to pump light in OPO, which changes the back conversion process [15]. By appropriately improving the signal light transmittance of output mirror, the influence of back conversion on conversion efficiency is eliminated [16]. Such methods can suppress back conversion by increasing the cavity loss, and the parameters cannot be adjusted in real time based on the phenomenon of back conversion. The overall power density of the energy field is reduced, which indirectly reduces the conversion efficiency.

A novel optical parametric oscillator is proposed, that is, an electro-optically polarization mode converter (EO PC) is set in the resonant to change the polarization state of the parametric light and adjust the proportion involved in the oscillation. The experiment of energy regulatory structure is carried out, which confirm that such structure can compensate back conversion and adjust the output ratio.
2. OPO Energy Conversion

2.1 Back conversion regulation

The energy coupling of optical parametric oscillation under pulse pumping can be described by the time-dependent three-wave coupling equation.

\[
\frac{\partial}{\partial z} + \frac{1}{v_p c} \frac{\partial}{\partial t} E_p(t,z) = \frac{i\omega_d}{n_p c} E_p(t,z) E_s(t,z) \exp(-i\Delta k z) \tag{1}
\]

\[
\frac{\partial}{\partial z} + \frac{1}{v_s c} \frac{\partial}{\partial t} E_s(t,z) = \frac{i\omega_d}{n_s c} E_p(t,z) E_i(t,z) \exp(i\Delta k z) \tag{2}
\]

\[
\frac{\partial}{\partial z} + \frac{1}{v_i c} \frac{\partial}{\partial t} E_i(t,z) = \frac{i\omega_d}{n_i c} E_p(t,z) E_s(t,z) \exp(i\Delta k z) \tag{3}
\]

Where \(E_p, E_s, E_i\) are the electric field of pump light, signal light and idle light respectively. \(d\) is the effective nonlinear coefficient. \(\Delta k\) is the phase mismatch.

An optical parametric amplifier generates 1.47 μm and 3.84 μm parametric lights at 1064 nm pumping. According to the above three-wave coupling equation, the waveform simulation results of the output light under different injection conditions are shown in Figure 1. Figure 1 (a) shows the simulated waveforms of pumped light, signal light, and idler light at 3 mJ of 1064 nm and 1 mJ of 1.47 μm. The peak value of 1064 nm pump light is too high, and the 1.47 μm signal light waveform has a depression caused by the back conversion. The unsynchronism of 1.47 μm signal light and 1.57 μm idle light are caused by the uneven energy ratio during the oscillation. The idler light energy is reduced to 0.2 mJ, and the simulation waveform is shown in Figure 1 (b). The optical parametric amplifier undergoes positive conversion, that is, the 1064 nm pump light is consumed, and the 1.47 μm signal light changes synchronously with the 3.84 μm idle light. The above simulations have theoretically confirmed that optimizing the injected light can effectively suppress back conversion, adjust the gain ratio, and improve the output light waveform.

![Figure 1. Output waveform simulation of optical parametric amplifier (a)1064 nm:3 mJ, 3.84 μm:1 mJ (b)1064 nm:3 mJ, 3.84 μm:0.2 mJ](image)

2.2 Energy regulatory structure

According to the quasi-phase matching condition, only e-polarized pump light, signal light, and idle light can participate in optical parametric oscillation. An electro-optically polarization mode converter (EO PC) is constructed by applying an electric field in the Y direction of MgO: PPLN crystal, which can change the polarization state of transmitted light. An EO PC is placed in the OPO cavity to adjust the polarization state of the parametric light, so as to realize the regulation of the e-light polarization and adjust the proportion of the parametric light involved in the oscillation.

Figure 2 shows the energy regulatory structure. As shown in Figure 2 (a), a Nd: YVO₄ high-repetition-frequency acousto-optic Q-switched laser is used as the pump source. The cavity mirrors M1, M2 and M3 form a ring resonator. The coatings of the mirrors M1, M2, and M3 are shown in Table 1.
MgO:PPLN crystal and EO PC are respectively placed in the resonant cavity. EO PC rotates the polarization state of 1.47 μm parametric light. When the energy regulatory structure works, as shown in Figure 2(b), the 1064 nm pump light passes through the cavity mirror M1 and enters the MgO: PPLN crystal, where 1064 nm pump light convert into e-polarized 1.47 μm and 3.84 μm parametric light. 1.47 μm signal light passes through EO PC, and polarization state rotates θ. Then the 1.47 μm parametric light is reflected by the mirror M1 and injected into the MgO: PPLN crystal again. The e-light polarization of the 1.47 μm parametric light continues to participate in oscillation and gain amplification.

### Table 1. Coating of mirrors

| Mirror | Coating                                      |
|--------|----------------------------------------------|
| M1     | 1064 nm@HT, 1.47 μm / 3.84 μm@HR             |
| M2     | 1064 nm@HR, 1.47 μm@T=20%, 3.84 μm@HT        |
| M3     | 1064 nm/1.47 μm/1.57 μm/3.3 μm/3.84 μm@HR    |

Figure 2. Schematic diagram of energy regulatory structure (a) the structure; (b) the principle

#### 2.3 Electro-optic polarization mode conversion

When light propagates along the x-axis of the EO PC, only the perturbation in the x-direction is considered. In the slow approximation, the polarization coupled mode equations of o-light and e-light in the crystal are as follows:

\[
\frac{dA_1(x)}{dx} = -i\kappa(x) A_2 e^{i\Delta \phi x} \quad (4)
\]

\[
\frac{dA_2(x)}{dx} = -i\kappa^*(x) A_1 e^{-i\Delta \phi x} \quad (5)
\]

Where \( A_1 \) is the complex amplitude of polarization in the y direction (o light), and \( A_2 \) is the complex amplitude of polarization in the z direction (e light). Coupling coefficient \( \kappa(x) \):
The relationship between the e-light conversion efficiency $T$ of EO PC and the polarization state rotation angle $\theta$ is

$$T = \cos \theta = \left| \frac{A_2(L)}{A_2(0)} \right|^2$$

Where $A_2(L)$ is the e-light polarization of the emitted light, and $A_2(0)$ is the e-light polarization of the incident light.

Assuming that the center wavelength of EO PC is 1.47 μm, the MgO: PPLN crystal polarization periods are 19.7 μm, respectively. When the length of the MgO: PPLN crystal is 38 mm, the simulated values of the e-light conversion efficiency $T$ and polarization rotation angle $\theta$ under different electric fields are shown in Figure 3. As can be seen from the figure, by changing the electric field of the EO PC, the proportion of the e-light polarization can be controlled.

Figure 3. E light transmittance and rotation angle of EO PC

3. Experiment

The experiment of energy regulat ory structure is built. The 1.47 μm and 3.84 μm output power under different EO PC electric fields are shown in Figure 4. Among them, $E$ represents the electric field strength of the EO PC, the unit is V / mm; the ratio is the ratio of 1.47 μm to 3.84 μm output power. As shown in Figure 4(a), when the loading voltage of the EO PC is 180V / mm and the polarization state of 1.47 μm signal light does not rotate, the 1.47 μm output power is less than 3.84μm, and the 3.84 μm output power decreases with the pump optical power at high pump power, indicating that back conversion is triggered. In figure 4(b) and (c), when the loading voltage of EO PC is reduced, the polarization state of 1.47 μm rotates, and the signal light energy involved in the oscillation is reduced, resulting in the output power increasing with the pump power. The output power of 1.47 μm and 3.84 μm intersects. In figure 4(d), when the loading voltage of EO PC is 157V / mm, the output power of 1.47 μm is greater than 3.84 μm. When the 1064 nm pump power is 21 W, the output power of 1.47 μm and 3.84 μm are 4.4 W and 3.7 W, with a ratio of 1.2 This confirms that the energy regulation structure can inhibit back conversion and balance gain ratio.

![Figure 3. E light transmittance and rotation angle of EO PC](image)

![Figure 4. Output power and ratio of 1.47 μm and 3.84 μm under different electric fields](image)
4. Conclusion
A novel optical parametric oscillator based on an electro-optically polarization mode converter can change the polarization state of the parametric light and adjust the proportion involved in the oscillation. The polarization mode conversion of MgO: PPLN crystal is analyzed theoretically. The experiment of energy regulatory structure is carried out. When the applied voltage of electro-optically polarization mode converter is 157 V/mm, the maximum output power of 1.47 μm and 3.84 μm are 4.4 W and 3.7 W, with a ratio of 1.2. The results show a substantial improvement in the compensation of back conversion.

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