Study on energy field regulation of multiple optical parametric oscillator based on electro-optic polarization transform and difference frequency generation

Hang Liu1,2, Yuheng Wang1, Lujie Li2, Yongji Yu1, and Guangyong Jin1*

1 Jilin Key Laboratory of Solid Laser Technology and Application, School of Science, Changchun University of Science and Technology, Changchun 130022, China
2 Changchun China Optical Science and Technology Museum, Changchun 130117, China

Abstract. In this paper, an active regulation method of back conversion for multiple optical parametric oscillator energy field based on electro-optical polarization mode conversion and difference frequency generation is proposed. The strong gain parametric light is converted into the weak gain parametric light to ensure that the parametric light energy in the oscillating cavity is in equilibrium and the back conversion effect is suppressed. The active regulation method is analyzed by means of polarization coupled and difference frequency conversion, and it is concluded that the intensity of electric field loaded on crystal and the power density of difference frequency pump determine the parametric conversion efficiency. Compared with the passive inhibition method, the active regulation method has the characteristics of strong dynamic compensation ability with wide range of basic frequency optical pumping energy, and can greatly improve the conversion efficiency and peak power.

1. Introduction

One pair parametric photons is oscillating in optical parametric oscillator, while in multiple optical parametric oscillator multiple pairs of parametric photons oscillate simultaneously in the cavity. Multiple optical parametric oscillator is an effective way to obtain the multi-wavelength tunable laser [1-6], which has a broad application prospect in military multi-band laser interference countermeasures, optical difference frequency long-wave THz, double-comb spectroscopy, high-precision synchronous detection of environmental multi-component gases and other frontier technologies [7-9].

At present, based on ignoring the influence of fundamental-frequency pump pulse waveform, the loss of strong gain parameter in optical parametric oscillator can be increased by means of non-collinear matching, cavity structure optimization and adjusting coupling output transmittance, so the probability of back conversion can be reduced [10-12]. These methods are all passive. Once the parameters are determined, they can not be changed according to the back conversion in real time. Moreover, this way reduces the coupling field power density, and indirectly reduce the conversion efficiency. Especially for the MOPO multi-wave coupling process, this negative effect is more serious. A new method of active regulation of MOPO energy field by electro-optic polarization mode conversion combined with differential frequency generation is proposed. The corresponding structural parameters are optimized. Theoretically, it is verified that this method can suppress the sag of pulse waveform caused by back conversion under the pulse pumping mechanism, and can greatly improve
the conversion efficiency and the maximum peak power without considering the insertion loss.

2. MOPO active regulation

2.1 Structure

The active control method of reverse conversion is to convert the strong gain parameter light into the weak gain parameter light by electro-optical polarization mode conversion and difference frequency guidance technology under the condition that the total energy of the two groups of parameter light does not change, so as to ensure that the ratio of the light energy of the parameter light in the cavity is in an equilibrium state and realize the purpose of restraining reverse conversion.

![Fig. 1. Schematic diagram of the active regulation for MOPO back conversion](image)

Fig. 1 is a Schematic diagram of the active regulation for MOPO back conversion. As shown in the figure, 1064nm pump light vibrates in MgO:APLN 1 crystal to generate two groups of parametric light: 1.47 μm, 3.84μm and 1.57μm, 3.3μm. The e polarized 1.47μm and 1.57μm signal light reflected by the output coupling mirror M2 is decomposed into two polarized states (e-light and o-light) by rotating θ angle of the polarized state after MgO:APLN 2 crystal. In MgO:PPLN crystal the difference frequency conversion of e polarized 1.57μm signal light and 759.2nm generates e polarized 1.47μm signal light. Finally, all signal light is converted to low gain 1.47μm signal light by MgO:APLN 3 crystal, and the polarization state is converted back to e light polarization. Therefore, the polarization mode conversion induced by pressurized MgO:APLN crystal and the differential frequency generation of MgO:PPLN crystal jointly determine the conversion efficiency of 1.57-1.47μm, which affects the inhibition effect of active control suppression structure on reversal conversion.

2.2 Electro-optical polarization conversion

Assuming that light propagates along the x-axis of MgO:APLN crystal, the perturbation of medium in the x-direction is considered only. Under the slow approximation condition, the polarization coupled mode equations of o and e light in the crystal:

\[
\frac{dA_1(x)}{dx} = -i\kappa(x)A_2e^{i\Delta k} \\
\frac{dA_2(x)}{dx} = -i\kappa^*(x)A_1e^{i\Delta k} 
\]

Where, A1 is the complex amplitude of y-directional polarization (o-light) and A2 is the complex
amplitude of z-directional polarization (e-light). Coupling coefficient $\kappa(x)$:

$$\kappa(x) = \frac{\alpha^2 \mu_0}{2 \sqrt{k_1 k_2}} \Delta e \left( x \right) = \frac{\pi}{\lambda} \left( n_o n_e \right)^3 \gamma_s f \left( x \right)$$ (3)

The coupling coefficient $\kappa(x)$ of MgO:APLN crystal is a non-periodic step function which varies with the polarization structure $f(x)$. Its absolute value is constant and the sign is determined by the polarization direction of the crystal.

The incident signal light is e-polarized light, and the initial condition is $A_1(0) = 0, A_2(0) = 1$. The electric field component after passing through each domain is calculated by the iterative algorithm, and the final radio field component is $A_1(L), A_2(L)$. E-light transmittance T is the ratio of output e-light to total input light,

$$T = \left| \frac{A_2(L)}{A_2(0)} \right|^2$$ (4)

2.3 Differential frequency generation
In the steady-state small signal approximation, the electric field intensity of pump and signal light does not change with the distance of action in the differential frequency process, and the coupled wave equation can be simplified as follows:

$$\frac{\partial E_i}{\partial z} = i \frac{\alpha}{n_c} E_p E_s \exp(i \Delta k z)$$ (5)

Where, $E_p, E_s, E_i$ denotes the electric field intensity of pumping light, signal light and differential frequency light, and $\Delta k$ denotes the phase mismatch. $d(z)$ is the expression of the polarization periodic function along the propagation direction of the crystal. Integrate equation (5) to obtain the difference frequency photoelectric field intensity $E_i$,

$$E_i = i \frac{2 \omega d_{33} L}{n_c \pi} E_p E_s e^{i \Delta k_0 z}$$ (6)

$$= i \frac{2 \omega d_{33} L}{n_c \pi} E_p E_s e^{i \frac{\Delta k_0 L}{2}} \sin c \left( \frac{\Delta k_0 L}{2} \right)$$

Differential frequency conversion efficiency $\eta$:

$$\eta = \frac{I_i}{I_p} = \frac{32 d_{33}^2 L^2}{c \varepsilon_0 n_p n_e n_i \lambda_i^2} I_p \sin c \left( \frac{\Delta k_0 L}{2} \right)$$ (7)

3. Simulation and Analysis
A 1064nm pulsed laser was used as the MOPO pump source for the simulation. The cavity mirrors M1, M2 and M3 form a multi-optical parametric oscillating cavity, in which MgO:APLN 1, MgO:APLN 2, MgO:PPLN and MgO:APLN 3 are placed successively. MgO: PPLN and MgO: APLN 3 are bonded together. A 759.2nm laser as differential frequency pump source is placed outside the cavity. MgO:APLN 2 has the same polarization structure as MgO:APLN 3, and the loading voltage is in the opposite direction. Mirror M1 coating is 1064nm@HT, 1.4-1.7µm/3.2-4.0 µm@HR, Mirror M2 coating is 1064nm/1.4-1.7µm@HR, 3.2-4.0µm@HR, Mirror M3 coating is 759.2nm@HT, 1064nm/1.4-1.7µm@HR. The crystal parameters in the cavity are shown in Table 1.
Table 1. Crystal parameters

| Crystal                        | Dimension       | Temperature |
|--------------------------------|-----------------|-------------|
| MgO:APLN 1                    | 1×6×50 mm       | 25℃         |
| MgO:APLN2                     | 2×6×46.5 mm     | 50℃         |
| MgO:PPLN+MgO:APLN 3           | 2×6×(40+46.5) mm| 50℃         |

Compared with the experimental values of the passively suppressed structure, the output energy field of active regulation structure is simulated when the 1064 nm fundamental frequency light pump energy is 3.5 mJ and 5.0 mJ, as shown in figure 2 and 3. The crystal loading electric field intensity and differential frequency generation pumping power density of active regulation structure is optimized. Then the output pulse waveforms of 3.3 μm and 3.84 μm idle light energy field are close to each other, and the maximum peak power root mean square error (RMSE) is 0.08 and 0.06, respectively. It shows that the back conversion is effectively suppressed, and the output energy values of the two idle light are close to each other. Compared with the passive suppressed structure, the active regulation structure has a higher dynamic compensation capability of back conversion, which can restrain back conversion effectively in a wide range of fundamental-frequency optical pumping energy, and greatly improve the conversion efficiency and peak power.

![Fig. 2. Output energy fields with fundamental frequency pump light energy at 3.5 mJ (a)active regulation; (b)passive inhibition](image)

![Fig. 3. Output energy fields with fundamental frequency pump light energy at 5.0 mJ (a)active regulation; (b)passive inhibition](image)

4. Conclusion
In this paper, an active regulation method of back conversion for multiple optical parametric oscillator
energy field based on electro-optic polarization transform and difference frequency generation is proposed, in which the strong gain parametric light is converted into the weak gain parametric light to ensure that the energy ratio of parametric light in the oscillating cavity is in equilibrium and the back conversion effect is suppressed. The active regulation method is analyzed by means of polarization coupled and difference frequency conversion, and it is concluded that the intensity of electric field loaded on crystal and the power density of difference frequency pump determine the parametric conversion efficiency. Based on the energy conversion model of MOPO with pulse mechanism, the output energy field of the active regulation structure of back conversion without insertion loss is included that the intensity of electric field (RMSE) of the maximum peak power are 0.08 and 0.06. It shows that the active regulation method can effectively suppress the back conversion. Compared with the passive inhibition method, the active regulation method has the characteristics of strong dynamic compensation ability with wide range of basic frequency optical pumping energy, and can greatly improve the conversion efficiency and peak power.

References
[1] Huang, H. T., He, J. L., Liu, S. D., Liu, F. Q., Yang, X. Q., Yang, H. W., Yang, Y., Yang, H. (2011) Synchronized generation of 1534 and 1572 nm by the mixed optical parameter oscillation. Laser Phys. Lett., 8: 358-362.
[2] Zhang, T. L., Yao, J. Q., Zhu, X. Y., Zhang, B. G., Li, E. B., Zhao, P., Li, H. F., Ji, F., Wang, P. (2007) Widely tunable, high-repetition-rate, dual signal-wave optical parametric oscillator by using two periodically poled crystals. Opt. Commun., 272: 111-115.
[3] Breunig, I., Sowade, R., Buse, K. (2007) Limitations of the tunability of dual-crystal optical parametric oscillators. Opt. Lett., 32: 1450-1452.
[4] Wang, P., Shang, Y. P., Li, X., Shen, M. L., Xu, X. J. (2017) Multiwavelength mid-infrared laser generation based on optical parametric oscillation and intracavity difference frequency generation. IEEE PHOTONICS J., 9:1500107.
[5] Chang, J. H., Yang, Z. B., Lu, Z., Dong, S. C. (2013) A novel multi-wavelength mid-infrared difference frequency generation laser source based on PPLN. Chinese Journal of Lasers, 40: 1002009.
[6] Chou, M. H., Parameswaran, K. R., Fejer, M. M., Brener, I. (1999) Multiple-channel wavelength conversion by use of engineered quasi-phase-matching structures in LiNbO3 waveguides. OPT. LETT., 24: 1157-1159.
[7] Kawase, K., Hatanaka, T., Takahashi, H., Nakamura, K., Taniuchi, T., Ito, H. (2000) Tunable terahertz-wave generation from DAST crystal by dual signal-wave parametric oscillation of periodically poled lithium niobate. OPT. LETT., 25: 1714-1716.
[8] Jin, Y. W., Cristescu, S. M., Harren, F. J. M., Mandon, J. (2014) Two-crystal mid-infrared optical parametric oscillator for absorption and dispersion dual-comb spectroscopy. OPT. LETT., 39: 3270-3273.
[9] Klingbeil, A. E., Jeffries, J. B., Davidson, D. F., Hanson, R. K. (2008) Two-wavelength mid-IR diagnostic for temperature and n-dodecane concentration in an aerosol shock tube. APPL. PHYS. B, 93: 627-638.
[10] Liu, J. H., Liu, Q., Gong, M. L. (2011) Back conversion in optical parametric process. Acta Phys. Sin., 60: 024215.
[11] Anstett, G., Nittmann, M., Wallenstein, R. (2004) Experimental investigation and numerical simulation of the spatio-temporal dynamics of the light-pulses in nanosecond optical parametric oscillators. APPL. PHYS. B, 79: 305-312.
[12] Anstett, G, Wallenstein, R. (2004) Experimental investigation of the spectro-temporal dynamics of the light pulses of Q-switched Nd:YAG lasers and nanosecond optical parametric oscillators. APPL. PHYS. B, 79: 827-836.