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Numerical analysis for single-frequency nanosecond optical parametric oscillators and optical parametric amplifiers

Xiang Zhang, Chunhua Wang, Zhibin Ye, Yunxuan Qi, Chong Liu*, Zhen Xiang, Jianhong Ge

The State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Zheda Road No. 38, Hangzhou 310027, China

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ABSTRACT

We numerically analyze single-frequency nanosecond optical parametric oscillators and amplifiers. It shows that a single-frequency optical parametric oscillator requires a single-frequency pump wave and a seed source for injection locking. The power of the injection seed should be increased dramatically to maintain single-frequency output as pump energy increasing. The results numerically verify that high energy and single-frequency output waves can hardly be reached simultaneously by optical parametric oscillators. Multistage optical parametric amplifiers are helpful to meet the shortcoming of optical parametric oscillators. During the amplification, the pump energy should match the signal energy in optical parametric amplifiers to obtain high conversion efficiency.

1. Introduction

Infrared waves have been widely used nowadays. It is known that optical parametric oscillators (OPOs) and optical parametric amplifiers (OPAs) are effective devices to generate near-infrared and mid-infrared laser waves. The nonlinear process in an OPO or OPA is called three-wave parametric mixing [1]. According to the difference of their frequencies, the three waves are called pump wave, signal wave and idler wave, respectively. The requirements of OPOs become specialized with their widely applications, which leads to the diversification of them. Near and middle infrared waves are needed in gas detection. The specific requirement in spectroscopy is narrow bandwidth and high spectral purity to ideally match the absorption features of the different trace gases [2]. There are many experimental researches on this kind of OPO [3–8].

Especially, differential absorption lidars (DIALs) developed rapidly these years [9,10]. For example, spaceborne integrated path differential absorption (IPDA) lidar technique is an effective means for the global column-averaged CO_2 concentration measurement with high precision and low bias. These systems deliver 1.57 μm or 2.05 μm single-frequency pulsed laser beams with pulse duration of several nanoseconds. Spectral aspects of the lasers play a major role in these IPDA lidar instruments. The spectral bandwidth, stability and purity requirements are extremely demanding. Pulse energy and pulse peak power are also important. Single-frequency nanosecond OPOs and OPAs are usually used to provide such laser beams. A single frequency pump wave is the common feature of these single frequency OPOs. Simultaneously, a continuous wave (CW) seed source is required for seed-injection locking of OPOs. In contrast, OPAs are much simple in these researches. It seems to be that the requirement for a narrow bandwidth OPA is a single frequency pump wave only.

In this contribution, we present our numerical simulation results of single-frequency nanosecond OPOs and OPAs. The emphases are focused on the spectral bandwidth of the output beam and conversion efficiency of these devices. The second section takes a simple review of the model we used here, introduced by Smith [11–13]. Numerical model for OPOs and OPAs has been found long before [14]. The early model ignores the depletion of the pump wave in optical parametric process, which is impossible in reality. The depletion, transverse electric field distribution of three mixing waves has been considered in subsequent models developed by Smith et al. [11–13]. The third section demonstrates OPOs operated under different conditions. We show that the output signal wave from OPOs might not be single-frequency, even if they are pumped and seeded by single-frequency waves. The simulation verifies that the power of seed waves needs to increase dramatically to keep single frequency output as pump energy increasing. So it would be unacceptable to obtain both high-energy and single-frequency infrared wave by OPO only. The forth section gives a solution of the problem. It is known that OPAs can overcome this shortcoming. But seldom researches mentioned the operating principles of OPAs. We

* Corresponding author. Tel.: +86 57187952193; fax: +86 57187952193.
E-mail address: chongliu@zju.edu.cn (C. Liu).

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show that the pump energy needs to be carefully arranged. When the signal pulse energy is given for an OPA, there would be proper pump energy correspondingly for the best conversion efficiency. Furthermore, simulation results show that multistage OPAs should be adopted to make full use of the pump energy. The pump laser should be properly divided into pulses with different energy for each stage. The proportion is determined by the temporal profile of output signal pulses. In the last section, conclusions are made for all the simulations.

2. Numerical model

The numerical mode used is mainly based on a planar-mirror resonator OPO shown in Fig. 1 as Smith did [11], including two mirrors and a crystal. We give a brief review of the model in this section. Incident pump wave enters the OPO from its left mirror. Incident signal wave and/or idler wave can also exist to simulate seeded OPOs.

The start point is the three-wave parametric mixing equations [11]

$$\frac{\partial}{\partial z}E_3 + \nabla_T^2 E_3 + \frac{1}{v_3}\frac{\partial}{\partial t}E_3 = \frac{2i\omega_3}{cn_3} d_{\text{eff}} E_1 E_2 e^{i\Delta kz} = P_3$$

$$\frac{\partial}{\partial z}E_1 + \nabla_T^2 E_1 + \frac{1}{v_1}\frac{\partial}{\partial t}E_1 = \frac{2i\omega_1}{cn_1} d_{\text{eff}} E_3 E_2^* e^{-i\Delta kz} = P_1$$

$$\frac{\partial}{\partial z}E_2 + \nabla_T^2 E_2 + \frac{1}{v_2}\frac{\partial}{\partial t}E_2 = \frac{2i\omega_2}{cn_2} d_{\text{eff}} E_3 E_1^* e^{-i\Delta kz} = P_2$$

The equations show that the mixing waves propagate along z-axis as time t increases. Subscript labels 1, 2 and 3 are symbols for signal, idler and pump waves separately in these equations. We only retain the slow varying temporal and spatial structure of electric field of the mixing waves and factor out the rapidly varying component of phase shift in this model. Habitually, c is the speed of light in vacuum, d_{eff} is the effective nonlinear coefficient, v_j is group velocity, and n_j is the refraction index (j = 1, 2, 3). Normally Δk is a constant called the phase-velocity mismatch of the three mixing waves defined by $\Delta k = k_3 - k_2 - k_1$. In this model, the three mixing waves can be continuous waves or pulse waves with their width longer than nanoseconds in time domain. For most cases, the pulse waves have Gaussian shape. But the input pulse of an OPA might not be Gaussian shape. It is determined by the former OPO or OPA output. This specific condition plays an important part in the forth section.

For the convenience of numerical solution, we introduce the new variables [15]

$$t' = (t - t_0) - \frac{z - z_0}{v_m}$$

$$z' = z - z_0$$

with t_0 and z_0 as arbitrary constants, where v_m is the fastest group velocity of mixing waves. To simplify the equations, we define that the start spacial point of OPO is $z_0 = 0$ and the very center point of the pulse in time domain is $t_0 = 0$. By introducing these new variables,

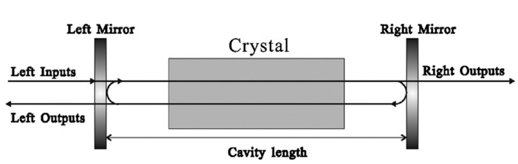

Fig. 1. Diagram of the optical parametric oscillator modeled in this paper. The reflectivity of mirrors can be changed to meet demands of users.

we can now give the linear propagation and nonlinear propagation equations in crystal

$$\frac{\partial}{\partial z'}E_j + \nabla_T^2 E_j + \left(\frac{1}{v_j} - \frac{1}{v_m}\right)\frac{\partial}{\partial t'}E_j = 0 \qquad (1)$$

$$\frac{\partial}{\partial z'}E_j = P_j \qquad (2)$$

with (j = 1, 2, 3). For the fastest wave ($v_j = v_m$), the linear propagation equation is a very simple partial differential equation without time factor. In another way, it is to say that the original point of t'-axis is moving as the fastest pulse moves in z'-axis. The time step Δt is equal to spacial step Δz_c in crystal divided by v_m and Δz_f in free space divided by c. In free space, the propagation equation only has linear part, which means Eq. (1) only. Meanwhile, in crystal, the propagation should contain two parts, a linear propagation part Eq. (1) and a nonlinear propagation part Eq. (2). There should be phase compensation of the two slower waves as they cannot propagate Δz_c in a single time step. So we add a phase shift $2\pi\Delta t\left(v_m - v_j\right)/\lambda_j$ on electric fields of all points on transverse plane of every step and ignore the electric field intensity variation of them. The equation for free space containing only linear propagation is solved by the split-step integration method [16]. We add nonlinear propagation sub-step in every linear propagation step to solve the equation for crystal. During every step of Δt, a certain percent (transmittance) of incident waves get into the OPO mode, while another certain percent (reflectance) of output waves get out the OPO. The outputs of every time step forms the final outputs.

3. Single-frequency nanosecond OPOs

In this section, we show our simulation results of a single-frequency nanosecond pulsed OPO. The numerical model and algorithm we used is as mentioned in last section. We use $KTiOPO_4$ (KTP) as the nonlinear crystal in the simulation. The temporal profile of pump pulses is Gaussian shaped. Other parameters used in our simulations are listed in Table 1 in detail as Smith did [17]. We lay the emphases on the spectral aspects of the output beam in the simulation.

A single-frequency pump wave is always essential in a single-frequency nanosecond OPO. However, without injection seed source, the signal pulse and idler pulse might not be single-frequency, because they start from quantum noise. We simulate the OPO under this condition and show its output in Fig. 2. It shows that the output signal pulse is very smooth when the OPO is operated near threshold. The spectrum can be obtained through Fourier transform. Fig. 2(b) shows that the output signal pulse is single-frequency near threshold even without seed injection.

When we increase the pulse energy of pump wave to five times threshold, the spectrum of the output from OPO becomes different. The output signal wave is multi-longitudinal-mode at five times threshold, in contrast to the single-mode output signal wave near

Table 1
OPO parameter table.

Parameters	Signal	Idler	Pump
Wavelength (nm)	800	1588	532
Refractive index	1.817	1.736	1.790
Pulse energy (mJ)			0–150
Power (W)	0–1		
Beam diameter (mm)	3	–	3
Pulse duration (ns)	cw	–	3
Left mirror reflectivity	0.99	0.99	0.00
Right mirror reflectivity	0.7	0–0.7	0.00
d_{eff} (pm/V)	3.2		
Cavity length (mm)	30		
Crystal length (mm)	10		