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A Phase-Controlled Optical Parametric Amplifier Pumped by Two Phase-Distorted Laser Beams *

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We theoretically study the phase characteristic of optical parametric amplification (OPA) or chirped pulse OPA (OPCPA) pumped by two phase-distorted laser beams. In the two-beam-pumped optical parametric amplification (TBOPA), due to spatial walk-off, both of the pump phase distortions will be partly transferred to signal in a single crystal so as to degrade the signal beam-quality, which will be more serious in high-energy OPCPA. An OPA configuration with a walkoff-compensated crystal pair is demonstrated for reducing the signal phase distortion experienced in the first stage and ensuring the signal phase independent of two pump phase distortions through the second crystal, hence maintaining the signal beam-quality. Such a TBOPA is similar to the conventional quantum laser amplifier by means of eliminating its sensitivity to the phase and number of the pump beams.

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With the rapid progress of laser technologies[1−3] and nonlinear crystals,[4,5] OPA has become a routine approach in obtaining tunable, high-power ultra-short pulses. Compared with the quantum laser amplifiers, optical parametric amplifiers (OPAs) do not involve any real energy levels, and a signal laser is amplified through the three-wave nonlinear interaction, in which any pump noise may directly distort the signal. While in the conventional laser amplifier, seed laser is amplified through the gain medium, pump laser only provides the energy for accumulating the population inversion, therefore, the beam quality of seed laser will not be affected by pump laser but mainly influenced by thermal effect of the gain medium. In the OPA process, besides the pump-intensity dependence,[6] pump phase distortion will be transferred to signal due to spatial walk-off so as to degrade the signal beam-quality. If pumping with two or multiple beams, signal will partly carry all the phase features of pump beams, and will further degrade the signal beam-quality. As a result, OPAs are quite sensitive to the phase and number of the pump beams. On the other hand, the conventional quantum laser amplifiers permit multiple pump beams to accumulate energy regardless of the quality and the number of pump beams. To date, great effort has been devoted to improving the capacity of OPAs and to exploring their capacity to perform like the conventional laser amplifiers. In this study, we try to reduce the sensitivity to the phase and number of the pump beam, and to ensure the signal beam-quality, so as to improve the performance of OPAs.

A basic feature of OPA is that the idler wave accumulates the phase difference between the pump and signal, which allows the use of the several pump beams to amplify a single signal.[7] A highly efficient parametric combining effect has been demonstrated in a three-beam-pumped OPA.[8] It has been proposed that high gain or high conversion efficiency can be achieved with multi crystals[9] and multi-pass amplification.[10,11] In the ultra-short pulse regime, multiple-beam pumped OPAs provide an extra degree of flexibility in extending and shaping the gain bandwidth by use of each of pump amplifying the neighboring spectrum region of the signal.[12,13] A high conversion efficiency and broadband tunable range have been shown by employing two noncollinear OPA stages.[14] OPA pumped by two incoherent pump beams shows its good performance in the picosecond pulse regime, including high gain, low signal wavefront distortion and energy stability.[15] However, in the studies of about two or multiple beams pumping, the impacts of the phase distortions or beam qualities of pump beams on the output signal beam are not considered. As a matter of fact, laser beam-quality and pulse contrast are of the key issues for laser systems, especially for high-energy laser systems.[16]

In this Letter, we mainly study the phase performance in the OPA or OPCPA process pumping with two beams. In the spatial domain, the nonlinear process of OPCPA is identical to that of the OPA, thus in most parts we do not make an explicit difference between OPA and OPCPA. We concern an issue related with pump phase distortion (irregular phase distribution in the transverse direction) as well as spatial walk-off. In the situation, the phase transfer from pump to signal may occur during the parametric process, which may degrade the beam-quality of signal. This kind of phase-noise transfer will be more serious in high-energy OPCPA, since high-energy pump lasers are typically with severe phase distortions and are far from diffraction limited.[17,18] If pumping with two beams, signal will carry the phase features of two

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pump beams and further degrade the signal beam-quality. Even if pump beams are with good beam-qualities, the output signal may be partially incoherent since the pump beams are typically independent in phase, which is unexpected in the practical laser system. Therefore, it is necessary for us to take the pump phase into account and to reduce pump-to-signal phase transfer so as to ensure signal beam-quality.

The walk-off compensated OPA scheme including a pair of nonlinear crystals with antiparallel optical axis,[19] for the sake of convenient adjustment, has been popularly employed to compensate for the walk-off so as to improve the conversion efficiency[20−22] and increase the acceptance bandwidth.[23] In this study, the walk-off compensated OPA scheme is applied to reduce the phase transfer, which makes signal phase independent of the pump source and maintains the beam quality of signal. Although pump-to-signal phase transfer occurs in each OPA stage, the phase of the final amplified signal may be restored to its initial value attributing to reverse spatial walk-off in the two successive crystals. Whatever two pump beams are coherent or not, we can obtain coherent signal beam. Such a TBOPA has been demonstrated to be insensitive to the phase and number of the pump beams and is very similar to the conventional quantum laser amplifiers in the phase aspect.

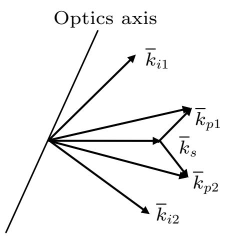

Fig. 1. Geometry of the noncollinear phase matching in TBOPA.

In the process of TBOPA, two pump beams in different directions amplify the signal simultaneously and generate idler beams, respectively, with the noncollinear phase matching (see Fig. 1). The noncollinear angle between two pump beams is chosen to be very small. The noncolinear phase matching permits all the beams propagating independently and avoids the interaction each other, which also make it easy to separate the amplified signal in the output. Similar to the three coupled-wave equations in the slowly varying envelope approximation,[24,25] considering the noncollinear, type-I (ooe) phase matching, the (1+1)-dimensional numerical model governing the evolution of the five beams reads

$$\frac{\partial E_S(z,x)}{\partial z}+\frac{L_{\rm NL}}{L_{sp1}}\frac{\partial E_S(z,x)}{\partial x} = -i\frac{\lambda_p}{\lambda_s}\sum_m E_{pm}(z,x)E_{im}^{*}e^{-i\Delta k_m z}, \quad (1)$$

$$\frac{\partial E_{im}(z,x)}{\partial z}+\frac{L_{\rm NL}}{L_{imp1}}\frac{\partial E_{im}(z,x)}{\partial x} = -i\frac{\lambda_p}{\lambda_i}E_{pm}(z,x)E_s^{*}(z,x)e^{-i\Delta k_m z}, \quad (2)$$

$$\frac{\partial E_{pm}(z,x)}{\partial z}+\frac{L_{\rm NL}}{L_{pmp1}}\frac{\partial E_{pm}(z,x)}{\partial x} = -iE_s(z,x)E_{im}(z,x)e^{i\Delta k_m z}. \quad (3)$$

In the above coupled-wave equations, we take one of the two pump beams (p_1) as a reference. Here E_n is the field envelop normalized to the input pump (p_1) field E_0, $n = p_m$, s, i_m, refer to two pumps, signal, and two corresponding idlers respectively, $m = 1, 2$ is the number of pump beam. The space variable x is normalized to the radius of pump (p_1) waist w and $\Delta k_m = k_{pm} - k_s - k_{im}$ is set to be zero, z is the longitudinal coordinate. The nonlinear length $L_{\rm NL} = n\lambda_{p1}/(\pi\chi^{(2)}E_0)$ is used to measure the pump intensity. $L_{np_1} = w/\rho_n$ is the walk-off length of other four beams to the pump beam p_1, and ρ_n is the walk-off angle, caused by both of the noncolinear phase matching and the deviation of extraordinary light from ordinary light in the crystal. The ratio of L_{np_1} to crystal length L indicates the practical walk-off magnitude of the OPA process, and the smaller L_{np_1} is, the larger practical walk-off magnitude will be. The diffraction has little impact and actually can be ignored in typical OPA cases since the diffraction length is very much larger than the crystal length. For example, a beam with a typical radius of 2 mm, wavelength 1 µm and beam-quality $M^2 = 10$ will have a diffraction length of about 2.5 m, which is much longer than the typical crystal length (1–2 cm) used in existing systems. For numerical simulations, the split-step method and Runge–Kutta algorithm are employed.

Since OPA is an instantaneously responded amplifier, any pump noise may directly distort both the signal and idler. Due to the intensity-dependent gain, the temporal profile of amplified pulse is susceptible to the intensity fluctuations of the pump pulse.[6] Though less appreciated, the pump phase-noise may also be partly transferred to the signal due to the effect of walk-off.[25] In the absence of walk-off, the generated idler wave bears the phase difference between pump and signal waves, fulfilling a relationship $\phi_s = \phi_{pm} - \phi_{im} - \pi/2$, and the phase of amplified signal will be independent of the pump phases and maintains the initial phase of incident signal,[7,8] which allows the use of the several pump beams to amplify a single signal. However, if walk-off exists, the phase profiles of pump and idler will be relatively shifted in transverse, thus their phase difference will no longer be constant. As a consequence, two pump phase noises will be transferred to both the idler and signal waves.

Firstly the impact of walk-off on signal phase with two phase-distorted pump beams is addressed. For simplicity, we assume the forms of two pump beams with sinusoidal phase modulations as $E_m(x,0) =$

$E_0 \exp(-x^2 + i\,a\sin(n\pi x))$, where the parameters a and n correspond to the modulation amplitude and spatial frequency, respectively. We set n to be different integers in the following calculations, but it is unnecessary to do so in general. Figure 2 shows the phase distribution of output signal in a single OPA stage with two different pump phase modulations in the case of spatial walk-off. It can be seen that two pump phase noises partly transfer to the signal wave due to spatial walk-off. The signal experiences the phase distortion from the combining effect of two pump phase modulations, which leads to an irregular phase shape of the output signal (Fig. 2). The magnitude of transferred signal phase depends on both the phase modulation frequency of pump beams and the walk-off.

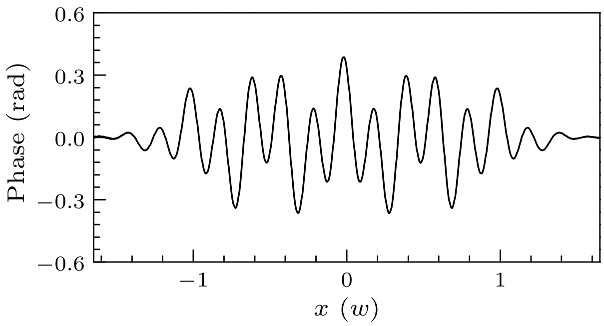

Fig. 2. Output signal phase distribution at the first OPA stage. Here $\phi_{p1} = 0.4\sin(4\pi x)$, $\phi_{p2} = 0.6\sin(10\pi x)$, $L_{sp1} = L_{imp1} = 50\,\mathrm{mm}$, $L_{\mathrm{NL}} = 0.4L$, $L = 8\,\mathrm{mm}$, $E_s(0) = 10^{-6}$.

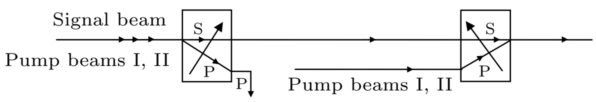

Fig. 3. Schematic diagram of a walkoff-compensated crystal pair.

The above studies show that pump-to-signal phase transfer is inevitable in TBOPA, and will be further enhanced in a multi-stage OPA system. Therefore, in the following, we will study a walkoff-compensated OPA configuration pumping with two beams to reduce this pump-to-signal phase transfer.

The OPA configuration using walkoff-compensated crystal pair is schematically shown in Fig. 3. The optical axis of a crystal pair are set to be antiparallel, so that the walk-off direction is reversed in the second crystal.[19] The two crystals in the walkoff-compensated OPA configuration may be considered as a single OPA stage, in which both the crystal length and pump intensity for the two crystals should be the same for optimally reducing the pump-to-signal phase transfer. The incident pump beams and signal beam are centered at the same position at the entrance of the first crystal. In the numerical simulations, the case of OPA with walk-ff compensation (opposite walk-off direction in the second crystal) is described by just changing the sign of the walk-off length (i.e., $-L_{np1}$).

Considering that the noncollinear angle of the pump beams relative to signal beam is very small, we simply ignore the nonlinear angle in the simulations. Figure 4 presents the results of output signal phases in the walkoff-compensated configuration and ordinary two-stage OPAs (i.e., identical orientation of the crystal axis). Because of spatial walk-off, output signal from the first stage (black solid curve) partly carries phase distortions of the two pump beams and will be enhanced (red dot-dashed curve) in the second OPA stage if walk-off is not compensated for in the second stage. The situation will be completely different in the case using the walkoff-compensated OPA configuration (blue dashed curve). Though the pump-to-signal phase transfer still occurs in each OPA stage, the reverse of spatial walk-off in the second crystal makes the phase of the amplified signal resumed to its initial value.

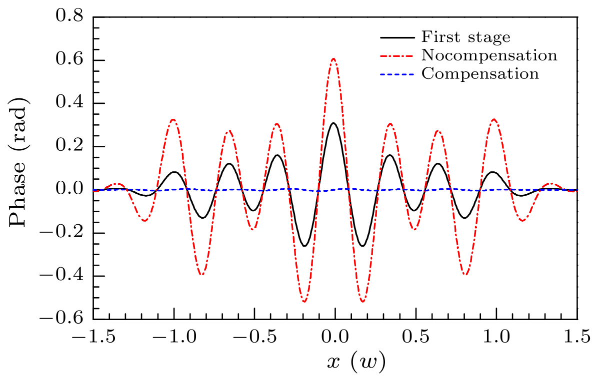

Fig. 4. Output signal phase distributions at the first stage (black solid curve) and at the second OPA stage with compensation (antiparallel optical axis) (blue dashed curve) and no compensation (identical optical axis) (red dot-dashed curve). Here $\phi_{p1} = 0.6\sin(4\pi x)$, $\phi_{p2} = 0.8\sin(6\pi x)$, $L_{sp1} = L_{imp1} = 50\,\mathrm{mm}$, $L_{\mathrm{NL}} = 0.5L$, and $L = 4\,\mathrm{mm}$, $E_s(0) = 10^{-6}$.

Laser beam quality is one of the critical factors in OPA or OPCPA laser systems. Since the phase aberration of a laser beam usually dominates the beam-quality, two pump beams considered here are assumed to be non-diffraction-limited due to phase aberrations. Beam-quality factor M^2, defined by Siegman,[26] is adopted. In order to show how the signal beam quality is affected by two pump phase distortions, we construct two non-diffraction-limited pump beams with $M^2_{p1} = 5$ and $M^2_{p2} = 10$, respectively. As shown in Fig. 5, the signal beam-quality after the first OPA crystal degrades (solid curve) as a result of phase distortion transfer from two pumps in the presence of walk-off. Due to the effect of walk-off compensation in the second crystal with antiparallel optical axis, the signal beam-quality from the second OPA crystal can almost maintain its initial value. It is important to point out that the signal beam-quality after the first OPA stage is not monotonically varied with the walk-off as shown in Fig. 5. Since we assume that pump phase distortion is a periodic modulation, thus the pump phase transfer also varies periodically. Nevertheless, any the induced phase distortion in the first OPA stage can be effectively reduced in the second walk-off compensated stage, and the final signal beam-quality after the second stage is diffraction-limited and does not varied with the walk-off values as shown in Fig. 5.

The parametric gains and conversion efficiencies in the two-stage OPA with the walkoff-compensated configuration and ordinary two-stage OPAs are present in Figs. 6 and 7. We can see that the overall OPA gain and conversion efficiency in the walkoff-compensated configuration is higher than that of the ordinary two-stage OPA, which attributes to the walk-off compensation in the second stage with the antiparallel optical axis. The efficiency simulation results for pumping with non-diffraction-limited beams agree with that of the cases pumping with diffraction-limited beam.[20−22]

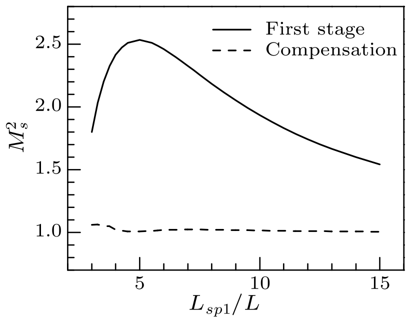

Fig. 5. Output signal beam-quality with different walk-off values. Here $M_{p1}^2 = 5$, $M_{p2}^2 = 10$, $L_{\rm NL} = 0.5L$, $L = 4$ mm, and $E_s(0) = 10^{-6}$.

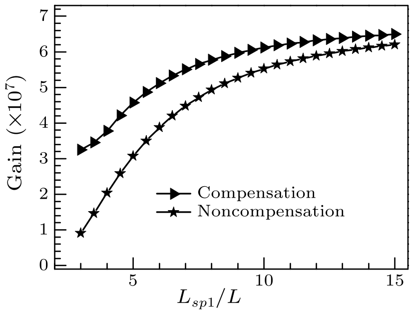

Fig. 6. Parametric gains in the two-stage OPA with walk-off compensation (antiparallel optical axis) and no-compensation (identical optical axis). $M_{p1}^2 = 5$, $M_{p2}^2 = 10$, $L_{\rm NL} = 0.5L$, $L = 4$ mm, and $E_s(0) = 10^{-6}$.

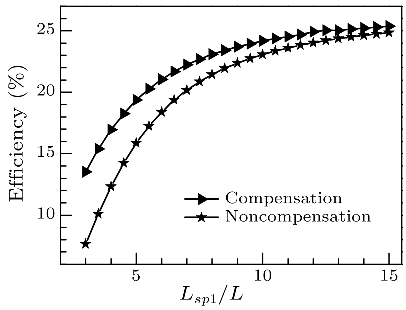

Fig. 7. Conversion efficiencies in the two-stage OPA with walk-off compensation (antiparallel optical axis) and nocompensation (identical optical axis). $M_{p1}^2 = 5$, $M_{p2}^2 = 10$, $L_{\rm NL} = 0.8L$, $L = 4$ mm, and $E_s(0) = 0.01$.

In conclusion, the combined effects of pump phase-noise and spatial walk-off will lead to the phase transfer from two pump beams to signal and degrade the signal beam-quality in TBOPA. Employing a walkoff-compensated crystal pair, the pump-to-signal phase transfer can be reduced and the phase of the final output signal can be almost resumed to its initial value, hence ensuring the beam-quality of the signal, which may be of importance for designing high-energy OPCPA systems. The OPA gain and conversion efficiency in the walk-off compensated configuration is higher than that of the ordinary two-stage OPAs attributing to reverse spatial walk-off in two successive crystals. By using the walkoff-compensated configuration suggested here, OPA is insensitive to the pump phase and number of pump beams and improves the OPA performance, which makes OPA very similar to the conventional quantum laser in the phase aspect.

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