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Theoretical studies on optimization of a broadband optical parametric amplifier for enhanced output stability

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ABSTRACT

In this paper, we report theoretical studies on optimization of a broadband optical parametric amplifier (OPA) with enhanced output stability for chirped pulse amplification. Optimization of various signal, pump, crystal and ambient parameters has been carried out to achieve an output energy fluctuation that is much smaller than the pump fluctuation. Different practical examples of single/multi stage OPAs and single/ multi pass OPAs, operating in many optical cycles and few optical cycles regimes have been considered in our studies. It is shown that apart from several crystal and beam parameter parameters, crystal temperature and inter/ intra crystal losses constitute important parameters which can be varied to achieve stable broadband pulse amplification in an optical parametric amplifier.

1. Introduction

Optical parametric amplifiers (OPA) have been extensively studied both theoretically and experimentally over several decades [1–7]. The application of the OPAs in the optical parametric chirped pulse amplification (OPCPA) scheme to built terawatt/ petawatt class ultra-short pulse laser system [8–25] have further boosted research in this field. A non-collinear OPA (NOPA) configuration [26–32] has been preferred over a collinear OPA configuration as it support wavelength tunable ultra-broadband amplification and offers easier implementation as the amplified signal beam is geometrically separated from the corresponding idler beam. The OPA offers high gain ultra-broad bandwidth over smaller temporal window (governed by the pump pulse duration) on a much smaller interaction length (crystal thickness), thus leading to a smaller material dispersion, smaller beam breakup i.e. B integral, larger pre-pulse contrast, and lower thermal effects compared to conventional laser amplifiers like regenerative or multi-pass laser amplifiers.

Unlike conventional laser amplifiers, the OPAs utilize instantaneous non-linear interaction of the signal and the pump beams. Hence the performance of an OPCPA system is expected to be highly sensitive to the temporal and the spatial overlap between the pump and the signal laser pulses inside the non-linear crystal. While the pump pulse duration has to be matched to the signal pulse duration in a single stage OPA, a much longer pump pulse has been used in multiple OPA or multi-pass OPA to achieve a maximum pump-to-signal conversion efficiency [33–37]. While pump pulse with a duration shorter than that of stretched signal pulse would result in an undesirable loss of amplified pulse spectrum in OPCPA, much longer pump pulse duration would result in poorer energy conversion efficiency. A spatio-temporal shaping of both the pump and signal laser beam with matched duration and beam size is often required to get an efficient broadband amplification [17]. In such cases, one would require precise synchronization between pump and signal pulses and a minimum error in the beam pointing. Further for ultra broadband pulse amplification, one often works with shorter duration pulses, as discussed in next paragraph. Pulse duration should not reduce below a certain value in order to avoid B-integral, and should not be increased above a certain value to avoid optical damage. In general, choice of pump pulse duration is then a trade-off between reasonable stretching ratio of the signal pulse, gain, bandwidth, accumulated optical nonlinearity (i.e. B integral) and damage threshold of optical coating and materials.

As the gain of an OPA scales with pump pulse intensity, hence it is desirable to work with higher pump pulse intensities with minimum fluctuation to achieve a larger gain with an excellent shot-to-shot output stability. Further, in order to avoid optical nonlinearity and damage, the pulse intensity should be much smaller than damage threshold of optical coating and material. Next, a short length crystal shall results in a smaller accumulated phase mismatch and therefore shall yields a larger gain bandwidth to allow amplification of few optical cycle laser pulses. However, the pump pulse intensity in such cases has to be extremely high. Such a scheme of using thinner crystals pumped at much higher pulse intensities, have been used to achieve amplification of few optical cycle laser pulses [38–40]. Working at very high pump intensities is possible with shorter duration laser pulses as the

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damage threshold increases with decrease in the pulse duration. Therefore shorter duration pump laser pulses are used in few cycle laser pulse amplification.

Although, OPA can operate in both many as well as few optical cycle pulse amplification regimes, the requirements for OPA design parameters are slightly different in the two cases. However, most important parameters of any non-collinear phase matched OPA are to have an optimum non-collinear angle and phase matching angle for a given crystal, pump wavelength and pump pulse intensity to obtain broad band amplification. Apart from optimizing various parameters, several bandwidth engineering solutions have been adopted to achieve broadband OPA gain. Both narrow spectral bandwidth pump pulse in single or multiple color pump scheme and broad spectral bandwidth pump pulses with angular dispersion or temporal dispersion have been used in the past to achieve a broad or ultra broad spectral gain bandwidth for an OPA. In addition to have a broadband spectral gain of an OPA, the spectral profile of the signal pulse can also be tailored to achieve broadband amplified laser pulses. Another alternative promising approach to have efficient pulse amplification [41,42] is to use chirped quasi-phase matched OPA with nearly 100% pump depletion. In this approach, an ultra-broadband amplification is possible with suitably engineered quasi phase matched periods and segments; while a high conversion efficiency is possible via adiabatic frequency conversion in engineered nonlinear structures [43,44].

Next, it is highly desirable for any amplifier [45–48] that its output is stable against any fluctuation in the pump source or any change in the ambiance. For an OPA, it is known that for an optimized crystal length, one can achieve a highly stable output [48] with fluctuation much below the pump fluctuation. This point is termed as gain-stationary point. Likewise, one may obtain a bandwidth-stationary point, at which the gain bandwidth is maximum [49]. This is maximum achievable bandwidth using narrow bandwidth pump pulses even without additional bandwidth engineering solutions briefly discussed above. It is expected that any variation in the beam (pump or signal), crystal and ambient parameters may change the gain and bandwidth of an optical parametric amplifier. Hence, in order to achieve a highly stable broadband optical parametric amplifier in real laboratory conditions, it is desirable to study the effect of various parameters of the crystal, signal, pump and ambiance on the gain-stationary point and bandwidth-stationary point. In case of multi-pass/multi-stage optical parametric amplifiers, additional parameters such as inter pass or stage losses are also important and should be considered in designing efficient stable broadband and or ultra broadband OPA.

In this paper, we report theoretical studies on the optimization of an optical parametric amplifier considering geometrical parameters, pulse intensity, inter and or intra crystal losses, temperature, and phase mismatch in general. It is shown that the crystal temperature and loss are additional important parameters that may be varied to achieve stable pulse amplification in an optical parametric amplifier. The present analysis is useful in designing a highly stable, broadband, multi-pass, and multi-stage optical parametric amplifiers, wherein inter pass/stage losses constitute additional controls to obtain stable operation of optical parametric amplifier.

2. Non-collinear phase matching geometry

Fig. 1 shows a typical non-collinear phase matching geometry that is used to achieve broad bandwidth gain for the signal laser pulse. In Fig. 1, α is the non-collinear angle between the pump and the signal wave vector, β is the angle between the pump and the idler wave vector, θ is the angle between the pump beam and the crystal optic axis, and ρ is the pump beam walk-off angle. The parameter $\delta\beta$ is the angular dispersion of an idler beam arising due to physical constraints as given below. The energy and momentum conservation in such a three wave parametric interaction results in following constraints [1,2]

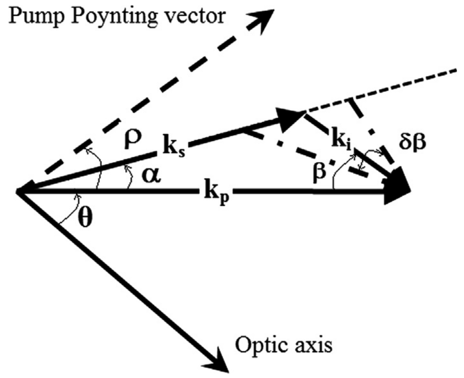

Fig. 1. Schematic geometry of the non-collinear optical parametric amplification.

$$w_p = w_s + w_i \tag{1}$$

$$\mathrm{k_p = k_s \cos(a) + k_i \cos(b)} \tag{2a}$$

$$\mathrm{0 = k_s \sin(a) - k_i \sin(b) i.e. b = \sin^{-1}[k_s \cos(a)/k_i]} \tag{2b}$$

where ω_p, ω_s and ω_i are the angular frequencies and $\mathrm{k_p}$, $\mathrm{k_s}$ and $\mathrm{k_i}$ are the wave vectors of the pump, signal and idler beam respectively. The Eqs. (1),(2) can be solved for angle tuning curves to obtain phase matching angles for a given crystal and interaction geometry and these are readily available in literature e.g. [2]. One calculates the optimum values e.g. [2] of the angles α and θ for a given pump wavelength such that the wave vector mismatch and group velocity mismatch is minimized over a broad range of signal spectrum.

3. Gain equations of an optical parametric amplification

Following are the main coupled wave equations that have been used to calculate the spatial evolution of the signal, the idler, and the pump beam, and the output stability, for optical parametric amplification in a nonlinear crystal under slowly-varying amplitude approximation [2].

$$\frac{dA_s}{dz} = -j\frac{\omega_s d_{eff}}{n_s c} A_i^* A_p \ \exp(-j\Delta kz) \tag{3a}$$

$$\frac{dA_i}{dz} = -j\frac{\omega_i d_{eff}}{n_i c} A_s^* A_p \ \exp(-j\Delta kz) \tag{3b}$$

$$\frac{dA_p}{dz} = -j\frac{\omega_p d_{eff}}{n_p c} A_s A_i \ \exp(j\Delta kz) \tag{3c}$$

where A_s, A_i, and A_p are the amplitudes of the signal, idler and pump beams, at a distance z within the nonlinear crystal, d_{eff} is the effective nonlinear optical coefficient that depends on the propagation direction and the polarization of the beam, and $\Delta \mathrm{k = k_p - k_s \cos(\alpha) - k_i \cos(\beta)}$ is the wave vector mismatch, $\mathrm{n_s}$, $\mathrm{n_i}$, $\mathrm{n_p}$ are the effective refractive index of the signal, idler and pump beams, and ω_s, ω_i, ω_p are the corresponding angular frequencies. Eqns. (3a–c) can be solved analytically for initial signal beam with amplitude A_{so} and no initial idler beam $A_{io}=0$, and for negligible pump depletion ($A_p \cong$constant). In this case, the signal beam intensity $I_s(z)$ and idler beam intensity $I_i(z)$ can be expressed as [2]