Cavity-enhanced optical parametric chirped-pulse amplification

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A novel method for the generation of high-energy ultrashort optical pulses is described and studied theoretically and numerically. Through the combination of parametric amplification and enhancement cavities, this method opens a route to generate few-cycle pulses at unprecedented average power levels through the use of a low-energy, high average-power pump source and energy storage in the enhancement cavity. Dispersion in the enhancement cavity ceases to be a concern with the use of long pump pulses. Limitations set by the Kerr nonlinearity of the amplifier crystal are analyzed, and ways to overcome them using self-defocusing nonlinearities are discussed.

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Several major developments have taken place in ultrafast science in the past several years. The generation of few-cycle pulses and the techniques related to carrier-envelope phase stabilization have enabled optical frequency metrology, attosecond physics, and extreme nonlinear optics. The development of robust and inexpensive techniques for the amplification of few-cycle pulses, especially to peak and average power levels exceeding the current limits, will have tremendous impact in diverse fields, including the generation of extreme ultraviolet and soft x-ray pulses through high-harmonic generation.

Lately there has been much interest in optical parametric chirped-pulse amplification[1] (OPCPA) as a method to amplify ultrashort pulses up to millijoule or higher pulse energies. Parametric amplification can be thought of as the utilization of an "engineered" gain medium, where the traditional energy states of an amplifying medium are replaced by virtual states arising from the coupling of the pump, signal, and idler beams through nonlinear polarization. As such, there is no storage of the pump light, necessitating synchronous pumping with comparable pump and signal pulse durations. The signal pulses are chirped to match the duration of the long and energetic pump pulse. Extremely large bandwidths can be achieved through noncollinear phase matching, and amplification of pulses as short as 6 fs has been demonstrated.[2] Ideally OPCPA can be scaled up to arbitrarily large pulse energies by increasing the beam sizes. The lack of storage of pump light eases thermal and material damage limitations. In practice, chirping the signal pulses much beyond several hundred picoseconds is difficult, with few nanoseconds being the upper limit, while still being compressible to a few optical cycles. The biggest difficulty is perhaps the need for a high-energy, high beam quality pump source with picosecond pulses. Since any imperfections of the pump beam are imaged to the amplified pulse, the pump laser must have excellent beam quality.

Recently, coherent addition of pulses in an enhancement cavity has been proposed and demonstrated as a method of pulse amplification.[3,4] Enhancement of optical fields in a resonator[5] is a commonly used technique, including femtosecond pulse addition for efficient second-harmonic generation.[6] However, this method gets increasingly difficult for short pulses as the intracavity dispersion may distort the mode comb and intracavity self-phase modulation leads to nonlinear distortions.[7]

In this Letter we propose a scheme that can be regarded as a conceptual combination of the OPCPA and enhancement cavity techniques (Fig. 1): the pump beam is coherently enhanced in an external cavity that contains a nonlinear crystal phase matched for parametric amplification of a signal pulse and is transparent at the signal wavelength. The stretched signal pulses are synchronized and time gated to overlap spatially and temporally with the pump beam. Once the cavity is loaded, the signal pulse undergoes parametric amplification. This way, signal pulses with a bandwidth supporting few-cycle pulses can be amplified without the limitations set by the cavity.

Cavity-enhanced OPCPA can be viewed as an extension of the analogy of parametric amplification to regular amplification one step further. The cavity assumes the role of pump light storage, with the product of the cavity round-trip time and the finesse corresponding to the gain relaxation time. In general, the pump source can be cw, Q switched, or a pulse train from a mode-locked laser; we focus on the case of a pulsed pump source.

Several major advantages can be identified. The pump light itself can be in the picosecond range or even longer, thus dispersion ceases to be a limitation to the enhancement cavity. With increasing finesse of

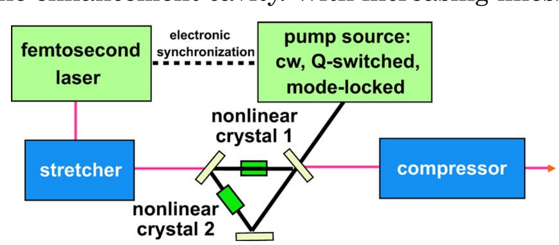

Fig. 1. (Color online) Schematic of the cavity-enhanced OPCPA. Nonlinear crystal 1 and (optional) nonlinear crystal 2 are for parametric amplification and nonlinearity management, respectively.

the cavity, the pump source has only to provide lower peak powers, opening up the use of laser sources that excel in high average power but are limited in peak power, such as fiber amplifiers, where 1 kW of average power has been demonstrated.[8] Unloading of the cavity is through a virtually instantaneous optical process, removing any restrictions on the cavity size due to finite switching speed. In fact, the cavity may consist entirely of a nonlinear crystal with appropriate dielectric coatings. Furthermore, the high-finesse cavity will act as an excellent spatial filter for the pump beam, ensuring a high beam quality, at the expense of a small amount of power loss. This point is important for maintaining the beam quality during parametric amplification.

The suggested cavity-enhanced OPCPA scheme requires the efficient buildup of an intense optical field circulating in a cavity, which is subject to nonlinearities and external driving. It is therefore natural to ask what are the fundamental limitations on this process. The goal of the rest of this Letter is to present a quantitative study of cavity-enhanced OPCPA. The Kerr nonlinearity poses a limitation on the energy enhancement that can be achieved and we propose a method to overcome it. Also, we show that the nonlinear driven system of an intense optical pulse circulating in the cavity is dynamically stable and does not seem to develop chaotic behavior.

The dynamics of the cavity-enhanced OPCPA can be understood in two largely independent steps that can be analyzed independently. During loading of the enhancement cavity, no light at the signal wavelength is present and the nonlinear crystal is a passive element. Once the cavity is fully loaded, the signal pulse is triggered to interact with the pump beam within the crystal. The repetition rate of the laser providing the signal pulses is reduced using a pulse picker or an acousto-optic modulator to match the desired unloading rate. Since the signal pulse passes through the cavity only once, parametric amplification is not influenced by the presence of the enhancement cavity. After unloading of the cavity, the entire sequence is repeated.

The energy enhancement factor depends on the round-trip losses of the cavity, with factors of ~ 1000 already reported for short pulses. However, any phase variations over the temporal profile of the pump pulses will cause the cavity modes to shift, limiting the enhancement. Therefore pump energy enhancement will be ultimately limited by the Kerr nonlinearity in the nonlinear crystal.[7] The nonlinear phase shift developing during the cavity buildup varies across the pulse. Therefore this phase shift cannot be compensated with feedback electronics tracking an average shift of the mode comb.

We show that enhancement factors approaching 50 and parametric gain larger than 20 dB can be realized without compensation of the Kerr-phase shift using periodically poled lithium niobate (PPLN), which already represents a significant advance. This is due to the favorable ratio between parametric gain g and self-phase modulation δ per unit length [which scales with the ratio of $\chi^{(2)}/\chi^{(3)}$] in PPLN. Gain is given by $G=0.25\exp(gl)$, where $g=4\pi d_{\mathrm{eff}}\sqrt{(2Z_0 I_p n_p)/(n_s n_i \lambda_s \lambda_s)}$ assuming ideal phase matching and $gl \gg 1$. Z_0 is the vacuum impedance. For PPLN, $g=5.2\sqrt{I_p/(\mathrm{GW/cm^2})}/\mathrm{mm}$. Thus, for an intensity of about 0.5 GW/cm^2 in a 2 mm long crystal, input to output gain of approximately 26 dB is achieved. Under these conditions the peak phase shift per round trip in the crystal is 5.6×10^{-3} which allows for an addition of approximately 50 pulses before the dephasing due to the nonlinear phase shift starts to prevent further buildup in the cavity.

We expect the technique of cavity-enhanced OPCPA to find use in experiments utilizing a range of crystals, gain factors, and peak powers. Hence we describe means to achieve even larger buildup factors using nonlinearity management[9] to overcome limitations due to the Kerr nonlinearity. In the past, several material systems have been identified to provide large negative ($n_2 \sim -1\times10^{-13}$ cm^2/W), self-defocusing Kerr-like nonlinearities.[10–12] In particular, cascaded quadratic nonlinear processes have been studied extensively, including soliton mode locking of solid-state lasers.[12] These processes correspond to second-harmonic generation in the presence of large phase mismatch. Energy loss due to residual second-harmonic generation can be kept well below 1% and does not appear to pose a significant limitation up to a cold cavity finesse of at least 100π. Compensation both in the temporal domain and in transverse space can be achieved,[13] which completes compensation of n_2 to first order for picosecond and longer pulses.

To test the validity of these expectations, we numerically simulated the loading of a cavity with a pulse train from a high-power laser at 1064 nm. The cavity comprises a 2 mm long β-barium borate, (BBO) crystal for parametric amplification and dispersion-compensating mirrors. A spot size of $r=60$ μm in a 2 mm long crystal with a bulk intensity-dependent refractive index $n_2=3.2\times10^{-16}$ cm^2/W results in a nonlinear phase shift per round trip of $\Phi=3.6\times10^{-2}$ rad/MW. Pulse propagation is described by the nonlinear Schrödinger equation with the cascade nonlinearity given by

$$n_2^{\mathrm{eff}} = -\frac{4\pi}{c\epsilon_o}\frac{1}{\lambda}\frac{d_{\mathrm{eff}}^2}{n_{2\omega}n_\omega^2}\frac{1}{\Delta k}.$$

For nonlinearity compensation, another BBO crystal of equal length is added for the cascade process. The benefits of nonlinearity management are illustrated in Fig. 2(a). In these calculations the pulse duration is fixed at 10 ps. For efficient operation the cavity is critically coupled, i.e., the transmittance of the coupling mirror is set equal to the remaining losses in the cavity, resulting in a cavity finesse of 100π. Without compensation, approximately 50 of the 10 kW peak power pump pulses at the input of the cavity can be added up to reach an intracavity pulse power of 0.5 MW for a peak nonlinear phase shift of $\Phi=1.8\times10^{-2}$ rad, which is comparable to the loaded

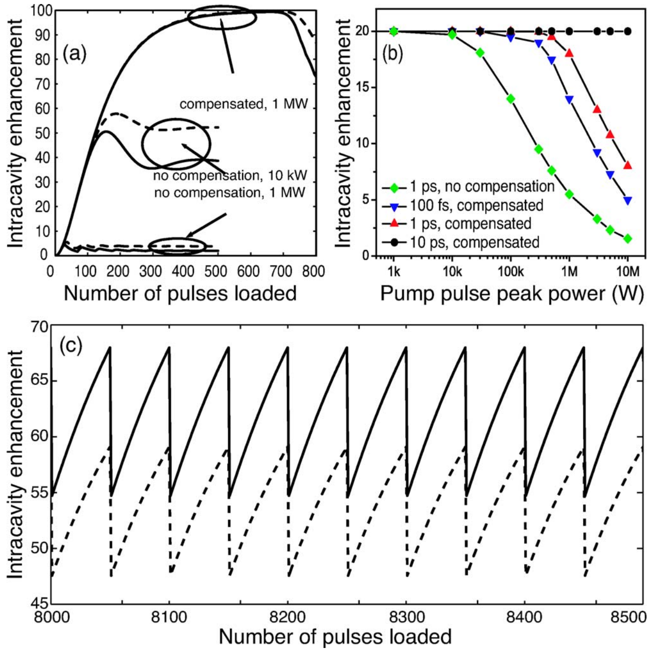

Fig. 2. (Color online) Results of numerical simulations: (a) Loading of the cavity with and without nonlinearity compensation. The solid (dashed) curves depict intracavity energy (peak-power) enhancement. (b) Intracavity buildup factor as a function of the peak power of the pump pulses with and without compensation of the nonlinearity. The lines connecting the dots are only a guide to the eye. (c) Oscillatorlike behavior of the passive cavity under pumping with a continuous train of pulses and periodic unloading. The solid (dashed) curves depict intracavity energy (peak-power) enhancement.

cavity amplitude decay rate per round trip of $1/\tau_A = 10^{-2}$. Due to the less favorable $\chi^{(2)}/\chi^{(3)}$ ratio for BBO, this leads to a maximum parametric gain of only 7.6 dB. Using nonlinearity compensation, pump pulses with even 100 times higher peak power (1 MW) can attain the theoretical limit of 100 times enhancement, which is much more than sufficient to extract good gain (for a peak power of 5 MW, a small-signal parametric gain of 37 dB is expected). As a control experiment, the use of 1 MW pulses without compensation is shown, leading to a buildup factor of less than 5. The capability afforded by nonlinearity compensation becomes crucial in experiments utilizing nonlinear crystals with less favorable ratios of gain to self-phase modulation.

However, for shorter pulses, the buildup process becomes complicated due to the interplay of nonlinearity and dispersion: perfect compensation of nonlinearity is not possible anymore since these effects do not commute.[9] In Fig. 2(b) we plot the cavity buildup factor achieved as a function of peak power of the pump pulses for pulse durations of 100 fs, 1 ps, and 10 ps, and employing nonlinearity management. Also plotted is the uncompensated case for 1 ps pulses (the pulse duration was found to be inconsequential in the absence of nonlinearity compensation). In all cases compensation improves the loading process dramatically at high powers, but the best results are obtained using the longer pulses, the case most relevant to cavity-enhanced OPCPA.

Thus far we have considered the case that at the beginning the cavity is completely empty. While this would be a common case for pumping with a finite train of pulses at low repetition rates, an interesting possibility is continuous pumping to optimize conversion efficiency. However, since the cavity is never fully unloaded and in the presence of nonlinearity and dispersion, it was not clear *a priori* whether phase errors within the cavity would build up over time, causing chaotic oscillations. Numerical simulations show that, for a wide range of parameters, continuous pumping is stable despite considerable pulse shaping [calculations covering 200 loading cycles are shown in Fig. 2(c)].

In conclusion, we propose a new technique, cavity-enhanced OPCPA, that is a conceptual combination of parametric amplification and energy storage in an enhancement cavity by coherent addition of pump pulses, as a practical route to high average and peak power sources of femtosecond optical pulses. The role of the cavity is analogous to the storage of pump light in an excited atomic state in regular amplification. The use of picosecond pump pulses eliminates dispersion-related problems during the cavity loading, while the signal pulse can have a broad bandwidth, permitting amplification of few-cycle pulses with proper phase matching. To reach extremely high energies, nonlinearity management in the enhancement cavity can be utilized, a concept equally applicable to passive coherent cavities and other nonlinear frequency conversion techniques, including high-harmonic generation. Practical implementation of this scheme using fiber lasers is under way.

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