23. Study on High Gain Broadband Optical Parametric Chirped Pulse Amplification

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Optical parametric chirped pulse amplification has apparent advantages over the current schemes for high energy ultrashort pulse amplification. High gain in a single pass amplification, small B-integral, low heat deposition, high contrast ratio and, especially the extremely broad gain bandwidth with large-size crystals available bring people new hope for over multi-PW level at which the existing Nd:glass systems suffered difficulties. In this paper we present simulation and experimental studies for a high gain optical parametric chirped pulse amplification system which may be used as a preamplifier to replace the current complicated regenerative system or multi-pass Ti:sapphire amplifiers. Investigations on the amplification bandwidth and gain with BBO are performed. Analysis and discussions are also given.

Key words: Broadband amplification, Ultrashort pulse lasers, CPA, OPA

1.INTRODUCTION

In the past few years, people recognized it is possible to amplify broadband optical pulses with a couple of well- developed nonlinear crystals such as LBO, BBO, KDP etc. through optical parametric process. However the extremely short pulse duration was still the main obstacle to higher efficiency. OPCPA [1-2] (optical parametric chirped-pulse amplification) technique came at the time when both chirped-pulse amplification (CPA) and broadband OPA had been well studied for many years. OPCPA is especially promising for the amplification of extremely short (even below 10fs) pulse from a few of micro-Joules to more than hundreds of Joules of energy with multi-PW output power by only several passes through the media, yielding small B-integral and good beam quality. Potential high contrast ratio is another unique advantage with OPCPA.

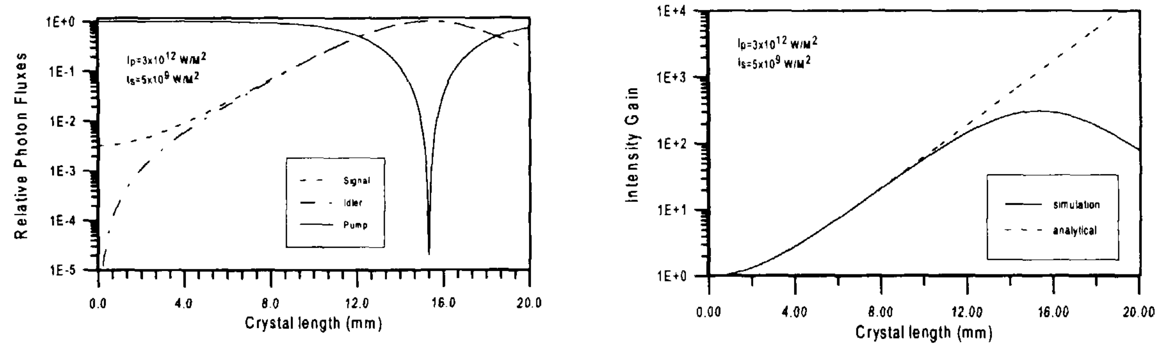
2.SIMULATIONS

We numerically solved coupled-equations [3] in order to have a full view on OPA. A program was developed to simulate the parametric interaction in a number of nonlinear crystals. There are input options available for both ordinary pulse and chirped pulse. In the case of chirped pulse amplification, given the temporal (or spectra and) inputs with arbitrarily distributions, different spectral components are first calibrated with respect to its temporal intensity counterparts which are then calculated separately and summed up over a certain length, yielding the parameters for all waves after interaction. The inputs include user supplied intensity distributions, spectral distributions, relative time delay, crystal and its length, angle for non-collinear scheme. Specific crystal parameters and characteristics such as phase matching angle, walk-off angle and spectral tuning can also be sorted with this program.

Typical simulation results are shown in Fig.1. Fig.1(a) refers to the amplification process in which a week signal and an idler grow exponentially in the small signal gain regime until the pump is fully depleted and therefore the amplification is saturated. It also gives a clear picture for the interaction after saturation, where energy begins to flow back to the bump and both signal and idler gradually dwindle. We compared our simulation with the results based on the analytical solution which omits the pump depletion as shown in Fig.1(b). They show good agreement with each other in the small signal gain region and remarkable deviation near and after saturation. This indicated that crystal length has to be carefully chosen once the parameters of pump and signal are set. The previous analytical analysis [2] is useful in small signal region but can not be used for selection of optimal crystal length, which is especially true in case of OPCPA where strong saturated amplification is expected in order to achieve high extraction efficiency and better stability. Previous efforts have been focused on seeking effective way to minimize the amplified spectral width and people had not taken much concern over the gain bandwidth until the amplification of femtosecond pulses emerged in the past few years. It turns out that this previous unwanted effect with OPA may be useful for broadband amplification. Fig.3 represents the chirped signal temporal profiles before and after saturation. Apparent broadening occurred in the strong saturation regime. It should be mentioned that temporal broadening in an OPCPA also associates with spectral broadening due to its unique chirped characteristics.

3.EXPERIMENTAL SETUP

The experimental setup is sketched in Fig.4. The whole system primarily consists of a femtosecond laser, grating stretcher, Nd:YAG pump laser and double stage OPA. The femtosecond laser source is a diode-pumped Nd:glass KLM oscillator with 100mW output power and 150fs pulse duration at 100MHz repetition rate. The FWHM spectral width is 8.2nm around central wavelength 1056nm. This laser shows excellent long period stability under our ultra-clean environmental condition. One of the femtosecond pulses is selected and temporally stretched to 1.2ns by a 4-pass stretcher comprising a 1480groov/mm grating, a concave mirror and some reflectors. Minor spectral clip occurred due to limited optics aperture, resulting in a reduction of spectral width to less than 8nm after the stretcher.



(a) (b)

Fig.1 (a) Signal gain and pump depletion, (b) Comparison with analytical analysis

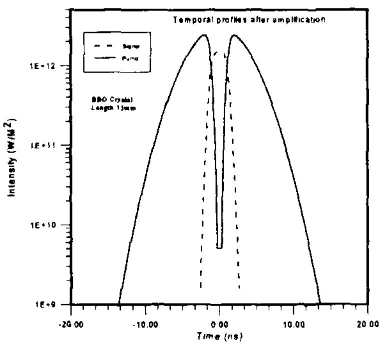


Fig.2. Temporal profiles of signal and depleted pump.

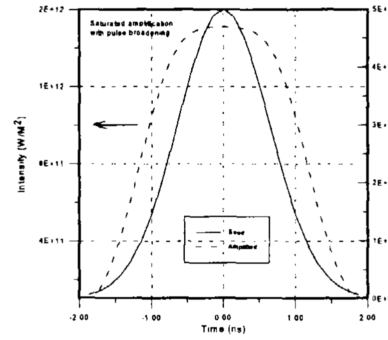


Fig.3 Signal temporal profiles before and after amplification

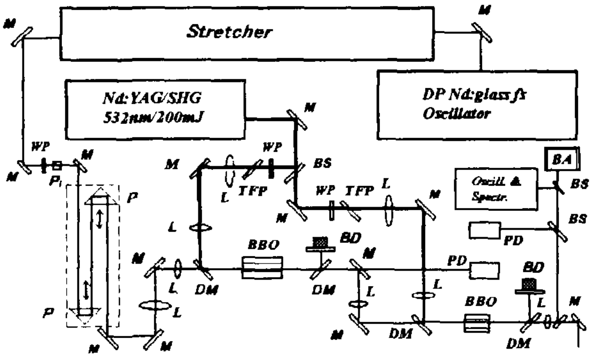
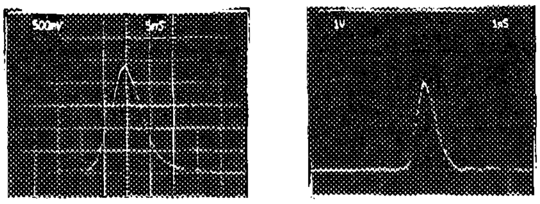


Fig.4. Schematic of experimental setup. M: reflectors; L: Lenses; WP: waveplates; P1: polarizer;P: prism reflectors; TFP: thin film polarizers; DM: dichroic mirrors; BD: beam dump; BS: beam splitters; PD: photo diodes; BA: beam analyzer.

The pump source for OPA in this experiment is a frequency-doubled/Q-switched and seeded Nd:YAG laser operating at 532nm with about 200mJ energy and 6 Hz repetition rate. This laser produces uniform flat-top beam pattern with better than ±2% shot to shot pulse energy stability and, most of all, fairly smooth temporal profiles which is crucial for OPCPA. As shown in Fig.5, the pulse duration is 8ns. Several polarisers and waveplates are used for allocation of pump energy while the uniform flat-top near field is image-relayed to the expected positions. According to our tests, no air breakdown was actually observed around the focus between the image-relay lenses for pump energy up to 80mJ in our laboratory. Pump beam sizes are demagnified about 4 times and pump fluence on crystals can be adjusted by changing either its energy or distance between imaging lenses. Seed pulse is electronically synchronized with the pump pulse in time. A set of optical delay line comprising corner-prisms and reflectors is also included in the schematic and turned out to be a good alternative for synchronization. This passive delay apparently has the advantage of simple structure and low cost but the disadvantage of its dependence upon the starting time of pump pulse. The seed beam is first demagnified and then combined with the pump beam by dichroic mirrors and spatially overlapped along crystal for efficient interaction. The focused seed beam is 0.3mm in diameter and is re-collimated by another lens after amplification.



(a) (b)

Fig.5. Temporal waveforms of (a)pump laser pulse, and (b)signal laser pulse.

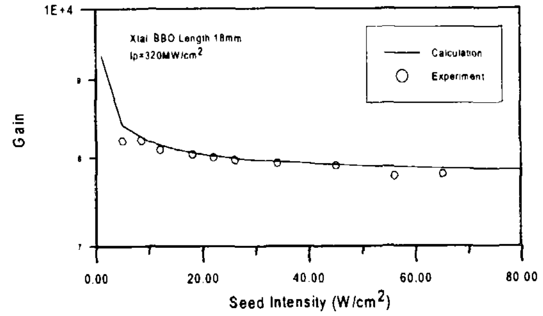


Fig.6. Gain dependence upon input signal intensity. Average data error is about ±10%.

BBO was used here as nonlinear crystal. BBO has higher non-linear coefficient but lower damage threshold and a relative larger walk-off in comparison with LBO. In addition, LBO shows broader bandwidth at certain conditions. In case of longer pulse pump like Q-switched YAG laser, BBO may be chosen for higher gain, especially on the first stage where a weak signal with tiny beam size is to be amplified The amplification gain and spectrum have been of top concern over OPCPA experiments. Both single and double-stage amplifications were performed. Two BBO crystals have the same 5mm× 5mm cross section and different lengths, one is 18mm long and another 14mm, respectively. For single crystal amplification, a relatively larger pump beam size insider crystal were chosen in order to keep the seed beam within the interaction area all along crystal length. According to our simulation, it is difficult for our weak signal to saturate the pump in a single pass before complete walk-off occurs even if the crystal is long enough. Lower pump fluence around 2.5J/ cm^2 was therefore kept to facilitate experiments. The measured pump diameter is 2mm and the actual pump fluence can be adjustable by simply changing the pump energy.

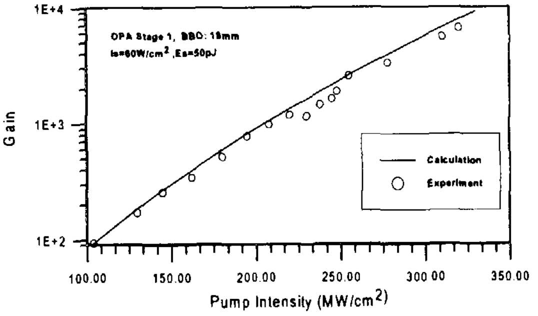


Fig.7. OPCPA gain dependence upon pump intensity and comparison with numerical simulations. Is: input signal intensity; Es: input energy. Average data error about ±10%.

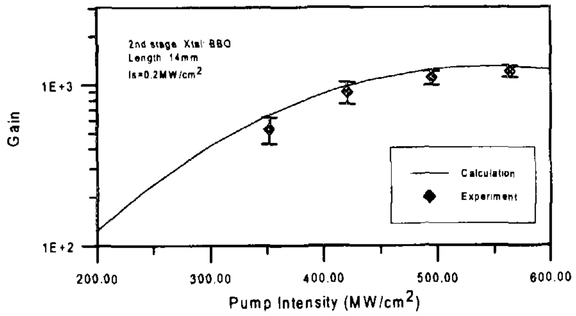


Fig.8.Double stage OPCPA gain dependence upon pump intensity. Is: input signal intensity

4.RESULTS AND DISCUSSION

We first examined the OPCPA gain dependence upon input signal intensity with the 18mm BBO. Because the overall throughput from the oscillator to OPA is about 10% and the signal energy can be changed from 100pJ down to less than 10pJ. As shown in Fig.6, the OPA gain keeps nearly constant for various input signal intensities when pump intensity is given. This is consistent with calculation and shares similarity with the conventional laser amplification process. With the same BBO we measured the gains under various pump intensities, as shown in Fig.7. The energy of input seed is 50pJ, corresponding to 60W/cm^2 intensity. The highest gain of 6600 was achieved with 320MW/cm^2 pump intensity which is the maximum available under present beam diameter and 80mJ energy in collinear configuration. Both experimental data and calculation clearly indicate the gain is still far away from saturation.

In order to increase the signal energy and amplification extraction efficiency, the 14mm BBO was used to form a second-stage OPA with basically the same configuration as the previous one. The output signal from the first stage served as the input signal to be amplified in the second stage. To prevent air breakdown, 80mJ maximum pump energy within a 1.5mm beam diameter was delivered to the crystal. The pump beam diameter, or the pump intensity, was carefully calculated with our computer code. It is important to keep in mind that the analytical theory can not be employed for estimation in this case where strong saturation was expected to happen. Fig.8 is the measured gains together with a simulation curve. Strong saturated gain of 1200 at this stage was obtained at 560MW/cm^2 maximum pump intensity. Taking into account of the 50% loss caused by mirrors and measurements between stages, the overall gain from two stage OPA reaches 1.4×10^7 and the final output energy is over 0.7mJ. If we calculate the OPA gain with respect to crystal length, our result shows that BBO has a gain of over 4×10^6/mm at the moderate pump intensity which is far more efficient than the widely used Ti:sapphire as broadband amplification media for the ordinary mJ level amplifiers. The extraction efficiency for the second-stage and whole system are about 0.9% and 0.45%, respectively.

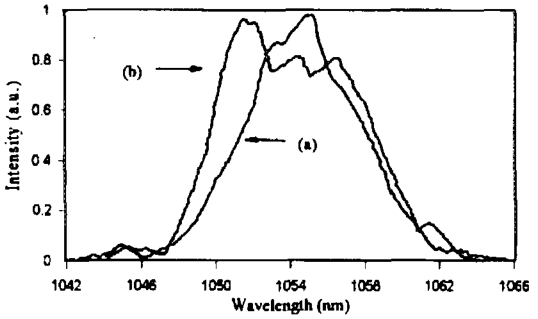
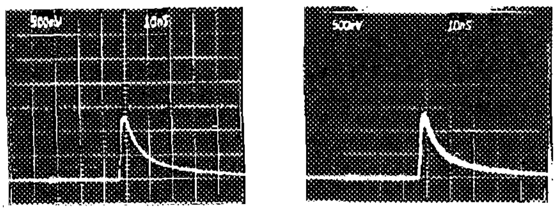


Fig.9. (a)seed spectrum and (b)amplified spectrum



(a) (b)

Fig.10. Traces of (a)single shot, and (b)60 shots pulses

The spectrum of one of amplified pulses was recorded as shown in Fig.9 with comparison with that of seed pulse. Little difference can be found between the original seed spectrum and the amplified from the first stage OPA where the gain is far away from saturation. Obvious flattening and broadening however appears under strong saturated amplification as in our case. We expect even more significant broadening for further amplification by adding a few more OPA for higher energy output since the gain bandwidth of BBO is beyond 100nm. For the sake of practicality to other applications, the output stability of OPCPA was examined. The oscilloscope photograph of both single shot and a typical overlap of 60 shots are shown in Fig.10. We estimated the final OPA output energy instability was less than ±5% while our pump laser has an output stability better than ±2%. It is certain that excellent environmental conditions partially contributed to the good OPA stability. In addition, our simulations shows there exits a optimal working point around the saturation area for the given crystal length and input signal, amplified output instability is minimized when the pump fluctuation varies within ±5%.

4.SUMMARY

Investigations were conducted both numerically and experimentally on the optical parametric chirped pulse amplification. Broadband amplification gain of over 1.4×10^7 in a single pass through two-stage BBO OPA were obtained with good output stability. Although the extraction efficiency is still low, this is not intrinsic and high efficiency of over 20% is possible with improved schematic according to simulations. OPCPA has great potential for amplifying extremely short pulses and is one of the ideal candidates for both high energy and high repetition rate ultrashort pulse lasers.

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