Improving the efficiency of an optical parametric oscillator by tailoring the pump pulse shape

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Abstract: The conversion efficiency of an optical parametric oscillator is reduced by energy consumption during build-up of signal and idler intensities and due to back-conversion effects. By tailoring the pump pulse temporal shape, we are able to improve the conversion efficiency by minimizing build-up time and back-conversion. Simulations predict a significant improvement in 1064nm to 4000nm idler conversion by using a double-rectangular temporal shape rather than using a simple Gaussian pulse. Experimental results qualitatively verify the effect resulting in a 20% improvement of a rectangular pulse over a Gaussian pulse.

OCIS codes: (190.4970) Parametric oscillators and amplifiers; (140.3510) Lasers, fiber.

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1. Introduction

An optical parametric oscillator (OPO) converts a pump laser beam with frequency ω_p into signal and idler frequencies, ω_s and ω_i, respectively, satisfying $\omega_s + \omega_i = \omega_p$. The conversion is based on difference frequency generation (DFG) that takes place in a non-linear crystal and is enhanced by oscillation of the signal and/or idler by mirrors. One signal and one idler photon are generated for each pump photon that is converted. Therefore the quantum limits for signal and idler conversion efficiencies are ω_s/ω_p and ω_i/ω_p, respectively, but in practice the efficiencies are much lower, approximately half of this limit. The reasons for this reduced efficiency include optical absorption, thermal effects, crystal quality, spatial beam profile, and other experimental difficulties [1]. In addition to these inevitable effects, long pulse OPOs,

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i.e., having long pump pulse duration compared to cavity round-trip time, have two additional effects that reduce the conversion efficiency that are related to the temporal dynamics of the three wave interaction.

(1) Buildup: The signal and idler waves are initially generated from quantum noise, which is then amplified to detectable levels. During this build up time, the pump power is not significantly depleted by conversion.

(2) Back-conversion: When the signal and idler are significantly increased the pump is depleted and the opposite process of sum frequency generation (SFG) occurs, in which signal and idler are back-converted into pump frequency.

In this work, a method is proposed to improve OPO conversion efficiency based on controlling the temporal shape of the pump pulse. By careful design of the pulse shape, the pump energy during buildup time can be minimized and back-conversion can be practically eliminated. Previous work on tailoring the pump pulse shape has been shown in [2] for an optical parametric amplifier. Adaptive pump pulse shaping in an OPO has been shown in [3] with the objective of decreasing nonlinear effects in the fiber pump laser by decreasing the peak pulse power and to shape the temporal and spectral output of the OPO. Up until now, no systematic study on how the pulse shape improves the OPO efficiency was made. Here we study theoretically the effects of the pulse shape on the OPO conversion efficiency for three typical pulses: Gaussian, rectangular, and double-rectangular. In addition, we measured the improvement of a rectangular pulse over a Gaussian pulse to verify the improvement shown in the theory.

2. Theory and simulation

Intuitively, the improved pulse shape is determined by following guidelines. The first part of the pulse should be short and intense, in order to reduce build-up time by increasing nonlinear gain. The second part of the pulse should have a constant, lower intensity, optimized for signal and idler conversion – strong enough for efficient signal and idler conversion, but not too strong in order to avoid back-conversion. The output intensities of the pump, signal, and idler beams are expected to be in steady state behavior during most of the second part of the pulse, and the OPO conversion efficiency is expected to be maximized, as in the case of optimal conversion of a CW OPO. According to these guidelines, the improved pulse shape may be "double rectangular," *i.e.*, two rectangular pulses adjoined, an intense short one followed by lower and longer one.

The investigation of the desired pulse shape and the OPO conversion efficiency was conducted by numerical simulations, using the split step method including diffraction [4]. The OPO chosen for this investigation was based on a 40mm long periodically poled $LiNbO_3$ (PPLN) crystal, placed in a linear cavity with two mirrors each with −50mm radius of curvature, separated by 65mm. The OPO configuration was single-pass pump singly resonant, *i.e.*, the output coupling mirror partially reflects the signal beam only and transmits the pump and idler. The pump, signal, and idler wavelengths were λ_p=1064nm, λ_s=1450nm, λ_i=4000nm, respectively. We started the simulation by setting the input conditions, namely the pump wave was defined in discrete time slots, separated by the OPO cavity round trip time (~0.74ns), the signal input wave was assumed to consist of only a single photon, and the idler input wave was zero. The transverse dependence of both the pump and signal was assumed to be Gaussian, and the waist location of the two beams coincided at the center of the crystal. The waist radii were matched to the OPO cavity, *i.e.*, 107.3µm for the signal and 91.6µm for the pump. We have then used the split-step method to solve the three coupled wave equations [4] of the pump at the initial time slot, signal and idler for the first passage through the nonlinear crystal. Typically, we used 300 steps in the crystal; hence the step size was ~133µm. Taking into account the transmission of the output coupler, we have obtained by this process the output wave powers at the first time slot. The calculation is now repeated for the following time slots, where the input conditions at the entrance to the nonlinear crystal are the

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signal wave that was generated in the previous time slot (after reflection by the output coupler) and the pump signal at the current time slot. Optimization was conducted with respect to idler conversion efficiency using a 65μJ pump pulse. In the following subsections, we show the improvements in idler conversion efficiency from a Gaussian pulse to a rectangular pulse, and, finally, to an optimized double rectangular pulse.

2.1 Gaussian pulse

Figure 1 shows simulations of pump, signal, and idler evolution for a 65μJ Gaussian pump pulse with duration of 60ns, full-width half maximum (FWHM). The output mirror has a signal reflection of $R_s = 90\%$ and high transmission for the pump and idler. One can easily see that the front of the pump pulse is not depleted due to lack of significant signal and idler intensity. After build-up is achieved, the conversion efficiencies are not constant and possess an oscillatory behavior due to back-conversion and the temporal shape of the pump pulse. The pump depletion is 40% and the overall idler conversion efficiency is 6.3%.

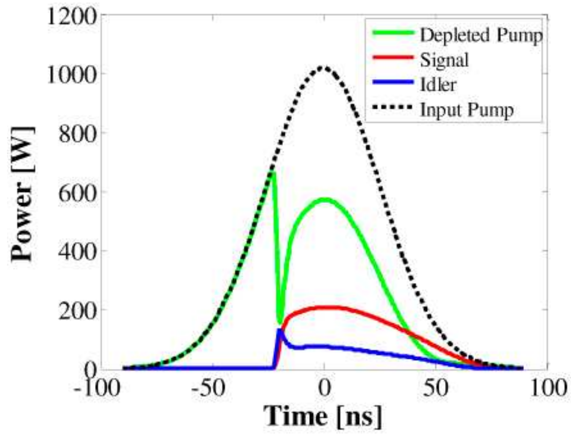

Fig. 1. OPO performance with a 60ns Gaussian pulse.

2.2 Rectangular pulse

For a rectangular pulse, we expect the following behavior: if the power level is below a threshold value, the conversion efficiency is zero. Above this level, the conversion efficiency will rise, but at a certain level back conversion will start to dominate. Hence, there is an optimum power level for conversion to the idler wavelength. This behavior is indeed observed in the numerical simulation as shown in Fig. 2a. An optimal idler steady state conversion of 17.2% was obtained with pump power of 150W (B). In this case, the 65μJ pump pulse had a duration of 443ns with 150W peak power. Overall idler conversion efficiency was 13.3% with pump depletion of 58.4%. This represents more than two-fold improvement in overall idler conversion efficiency with respect to a Gaussian pulse, under the same parameters of pulse energy, crystal length and cavity configuration. Figure 2b shows the steady state idler efficiency vs. position within the crystal for some selected power levels. For the optimal level (B), the idler power is maximized at the output face of the crystal. For the lower pump level (A) the conversion is too weak, whereas for the higher level (C) the conversion is maximized inside the crystal, but then back-conversion occurs. The time evolution of the pump, signal and idler pulses is shown in Fig. 3a. After approximately 100ns, the OPO output power, which starts from a single spontaneous parametric down conversion process, is amplified to a significant power level. This process is accompanied by depletion of the pump pulse. For the remaining ~300ns of the pulse duration, a constant level of signal, idler and depleted pump are maintained.

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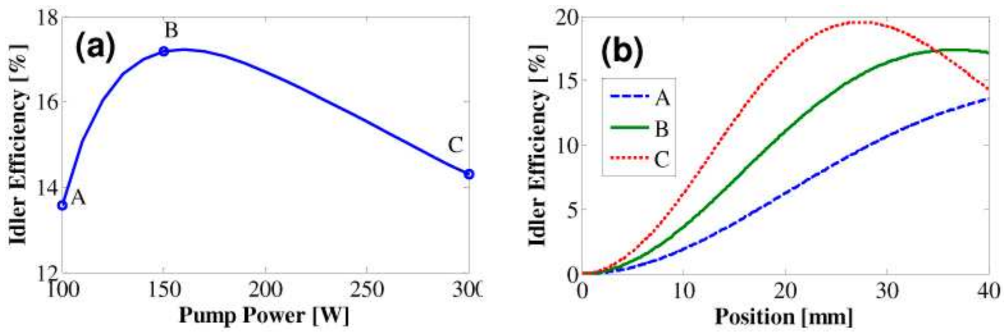

Fig. 2. OPO performance with a rectangular pulse. (a) Idler steady-state efficiency. (b) Steady-state idler efficiency within the crystal for pump power of (A) 100W, (B) 150W and (C) 300W.

2.2 Double rectangular pulse and optimization

Next, the energy in the build up portion of the pulse was minimized. The duration τ_1 and power $P_{buildup}$ of the pump pulse during build up can be estimated using the expression of signal power with undepleted plane wave pump [1]:

$$\frac{I_{th}}{I_{1-photon}} = \left[\cosh^2(\Gamma L)\cdot e^{-2\alpha L}\cdot R_s\right]^N \quad (1)$$

$I_{1\text{-}photon}$ is the initial one photon noise level; I_{th} is the signal threshold level; Γ is signal parametric gain which depends on pump power P_{p1} [5]; L is the crystal length and $e^{-2\alpha L}$ accounts for optical losses in a roundtrip. N is the number of times the signal oscillates until threshold level is reached, defined as $N=\tau_1/\tau_{rt}$, where τ_{rt} is the cavity roundtrip time. The pump energy consumed during build up is $E_{builup}=P_{buildup}\cdot\tau_1$. Using Eq. (1) the pump energy can be estimated, and pulse parameters $P_{buildup}$ and τ_1 can be optimized in order to minimize $E_{buildup}$. The optimal values of $P_{buildup}$=440W power level and τ_1=28.2 ns duration were found, with minimum energy of $E_{buildup}$=12.4 µJ consumed. However, simulations including a spatial Gaussian pump beam and diffraction showed that signal build-up is achieved with a shorter duration of τ_1 = 22.3ns: the consumed energy during build up is only $E_{buildup}$=9.8µJ. The discrepancy in build up time is due to plane wave approximation used in the Eq. (1), but nevertheless the plane wave results provide a good starting point for searching the optimal values. After $E_{buildup}$ is consumed, the remainder of the 65µJ pump energy is used for the second part of the pulse; its duration τ_2 is determined by dividing the energy by the optimal pump power level $P_{steady\text{-}state}$ which was found previously. The optimized pulse has a total duration of τ_{total}=390.3ns with $P_{buildup}$=440W, $P_{steady\text{-}state}$=150W, τ_1=22.3ns, and τ_2 = 368ns. The OPO performance with the optimized double rectangular pulse shape is shown in Fig. 3b, with total pump to idler conversion efficiency of 14.7%.

Table 1 summarizes the simulation results for the Gaussian, rectangular, and double-rectangular pulses, under the same pulse energy and cavity parameters. We have verified that even if we optimize the mirror reflectivity separately for each type of pulse, or change the pump pulse energy, we still get significant improvement by using a rectangular pulse and further improvement by a double-rectangular pulse, instead of a Gaussian pulse. For example, by increasing the Gaussian pulse energy to 100µJ or the output coupler reflectivity to 95% the conversion efficiency can increase only to ~11%, which is approximately half of the quantum limit and similar to published experimental values [6–8]. For comparison, increasing the double-rectangular pulse energy to 100 µJ (1800/675W for $P_{buildup}$, $P_{steady\text{-}state}$ in 11/89ns, respectively) can provide 16.3% conversion efficiency, provided we select R_s=45%.

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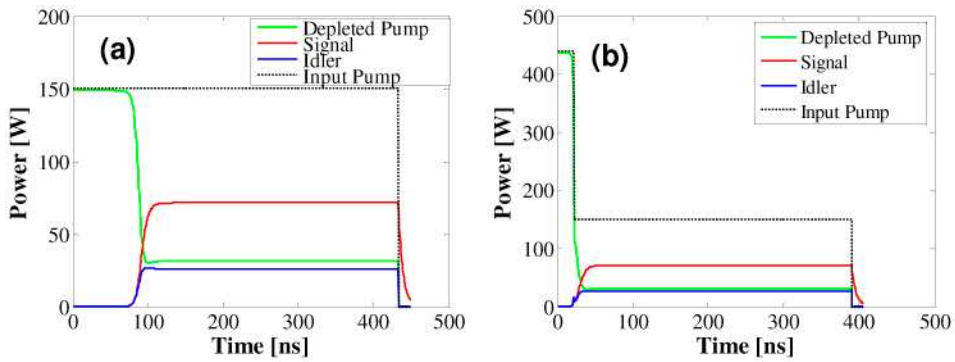

Fig. 3. Temporal evolution of pump, signal, and idlers pulses: (a) rectangular pulse, (b) optimized double rectangular pulse.

The double-rectangular pulse provides a significant improvement in the efficiency, and is fully defined by only four parameters (the power and duration in each on of the two sections of the pulse), which as we have shown can be systematically derived. Further improvements may be possible by using more sophisticated pulses, but the optimization procedure with such pulses will be more difficult, and in addition, it is harder to experimentally generate them.

Table 1. Pump Pulse Shape Optimization (R_s=90%, E_{pump}=65μJ)

Shape	Duration (ns)	Peak Power (W)	Pump Depletion (%)	Idler Eff. (%)	Idler CW Eff. (%)
Gaussian	60 FWHM	1018	40.0	6.31	–
Rectangular	433	150	63.4	13.3	17.2
Double Rectangular	22/368	440/150	66.6	14.7	17.2

3. Experiment

For experimental verification, a master oscillator power amplifier fiber laser was constructed with a controllable pump pulse shape [3,9]. The master oscillator consisted of a continuous wave amplified stimulated emission source (ASE) based on double clad ytterbium silica fiber, which was carved to a 40pm bandwidth centered at 1064nm using a fiber Bragg grating. The ASE was then amplified and then sent to a fiber coupled electro-optic modulator to perform the pulse shaping. A chain of an additional three amplifiers based on ytterbium silica double clad fibers of increasing core diameter were used to increase the pulse energy. The last stage consisted of a large mode area fiber amplifier pumped by 976nm diode bars. The output spectrum was broadened to approximately 0.1nm due to nonlinear effects, namely self-phase modulation. Spectral broadening can be reduced in future designs by decreasing the fiber length and increasing the mode field area in the last amplifier. For all pulses tested, no stimulated Raman scattering (SRS) was observed. As noted in [3], one of the main objectives of pulse shaping in a fiber laser is to decrease the peak power, thus minimizing or avoiding nonlinear effects.

Given the experimental difficulties, only Gaussian and rectangular pulses at the OPO input were studied. A 100ns Gaussian pulse and a 300ns rectangular pump pulse, as shown in Fig. 4a, were launched into the OPO previously described with an output coupler signal reflectivity of 95%. (As will be shown later by comparison to simulation, the higher reflectivity used in the experiment may account for additional losses in the OPO.) The OPO consisted of a 40mm long periodically-poled MgO:SLN crystal [10]. The OPO cavity was 65mm long, and consisted of an input mirror with high reflectivity for the signal and idler and high transmission for the pump. The pump beam was focused to the center of the crystal, and its waist size was ~100μm. The pump power was controlled using a polarizer and a half-wave plate before the OPO in order to keep a constant pump pulse shape and spectrum. Figure 4b

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shows the depleted pump and idler generated from the rectangular pulse input at maximum pump power. The buildup of the OPO power occurs in the first ~70ns.

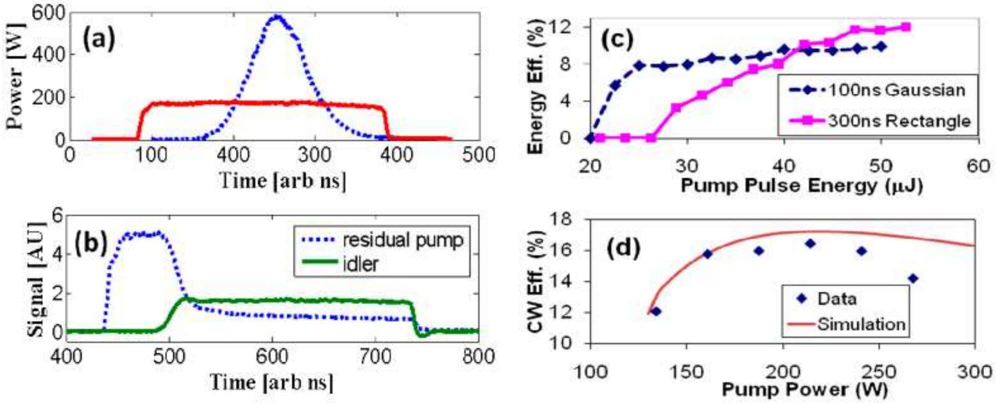

Fig. 4. OPO experimental results (a) Input pumps: Gaussian and rectangular. (b) Input and output OPO pulses in the case of rectangular pump pulse (c) OPO idler power curve for Gaussian and rectangular pulses. (d) Steady state idler conversion efficiency for rectangular pulse.

The efficiency curves for the Gaussian and rectangular pulses of Fig. 4a are shown in Fig. 4c. With the rectangular pulse, the threshold is a higher, owing mainly to the lower peak power. However, this rectangular pulse provides 20% higher energy conversion efficiency with respect to the Gaussian pulse. Further increases in efficiency can be expected by lengthening the pulse or by using a double rectangular pulse. Figure 4d shows the steady state efficiency: comparison of the steady state idler power to the pump power. The maximum steady state efficiency is approximately 16%, and it appears that the optimum occurs for a pump power around 225W. The existence of the optimum was predicted in Fig. 2a for an OPO of a slightly different configuration. In order to provide an approximate fit of the simulation to the experimental results, the output coupler was reduced R_s = 90% and d_{eff} to 10pm/V, which can be accounted for by additional cavity losses, poling imperfections, and pump laser bandwidth.

4. Conclusions

To conclude, we have presented a method of improving OPO conversion efficiency by controlling and determining the pump pulse temporal shape. We have outlined the considerations for reducing the buildup time and optimizing the steady-state conversion efficiency. The simulations predict an increase of up to 34% in conversion efficiency using this method from an optimized Gaussian pulse when the pulse energy is constrained in this particular OPO to 65μJ, or an increase in pump depletion from 40% to 67%. Experiments have shown a 20% increase in efficiency between a rectangular and Gaussian pulse. When free control is given over the pulse and cavity parameters, the idler efficiency can approach CW OPO efficiencies of ~17% or higher, which is more than a 50% increase in OPO efficiency over conventional pulses.

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