Experimental Demonstration of Efficient OPA via Simultaneous SHG

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ABSTRACT: We demonstrate dramatic parametric amplifier conversion efficiency enhancement simply by arranging for simultaneously phase-matched idler second-harmonic generation, with 44% pump-to-signal energy conversion (68% pump depletion) in a 48-dB-gain bulk-crystal mid-IR amplifier stage with Gaussian beams.

The efficiency of optical parametric amplification (OPA) is fundamentally limited by asynchronous spatiotemporal conversion due to the local dependence of the conversion cycle on the field intensity. For Gaussian beam and pulse shapes, the pump photon depletion efficiency is typically only 10-30% with only 1-20% of the pump energy going to the signal. This longstanding limitation dramatically raises the cost of entry for research involving high power and ultrafast lasers. Techniques such as flattop-profile and conformal profile pump shaping aim to improve efficiency by synchronizing conversion cycles [1-4], but the inefficiency, complexity, and cost of pulse shaping pose severe limitations. A recent technique of 'quasi-parametric amplification' demonstrated a significantly boosted conversion efficiency in a bulk crystal with a dopant added to induce linear absorption of the idler, suppressing back-conversion [5]. However, such methods reintroduce the constraint of operating at wavelengths corresponding to a material resonance, a constraint that OPAs are often used to circumvent.

Here, using only nonlinear parametric processes in an ordinary crystal for birefringently phase-matched OPA, we achieve an unprecedented 44% pump-to-signal conversion efficiency – even higher than that achieved with flattop pump beam and pulse shapes [1] – and with a high single-stage gain of 48 dB, a several-fold improvement to the ~12% efficiency ordinarily achievable. This constitutes the first experimental device demonstration of a newly predicted approach [6] that uses simultaneous second harmonic generation (SHG) phase matched at the idler wavelength in OPA to enhance the signal conversion efficiency via suppressed back-conversion while preserving the idler energy in a coherent copropagating field at twice its frequency (Fig. 1a,b). We also verify the underlying wave evolution dynamics, which have been theoretically described using a damped Duffing oscillator model where the idler SHG process, acting like an effective loss channel, induces a damped oscillatory exchange of energy between the OPA waves with asymptotically full convergence of energy to the signal and idler second harmonic (SH) fields (Fig. 1c) [6]. This enables synchronous spatiotemporal conversion of Gaussian field distributions, greatly enhancing the conversion efficiency of OPAs without using spatiotemporal shaping or material absorption.

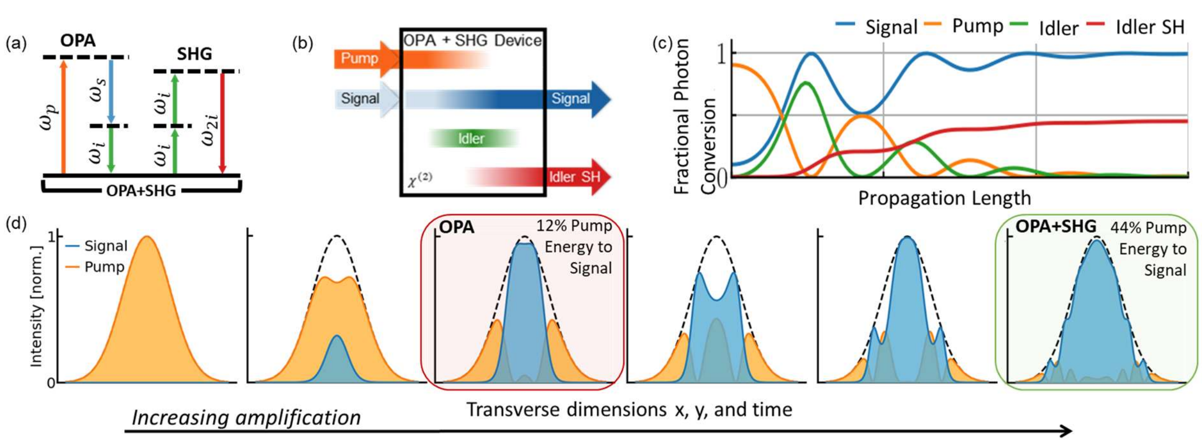

Fig. 1. (a) Virtual energy level diagram of OPA with simultaneous idler SHG. (b) Conceptual depiction of an OPA + SHG device with full conversion of the pump to the signal and idler SH fields. (c) The idler SH field (dashed purple) extracts energy from the idler field (green) leading to a damped oscillatory exchange of energy between the pump (orange) and signal (blue) fields. (d) 1D slices of a Gaussian spatiotemporal pump field distribution showing the OPA constraint of operating where just the peak of the distribution has fully converted (red box). Simultaneous SHG relaxes this constraint, enabling nearly full conversion to the signal field across the full spatiotemporal distribution (green box).

Our experimental demonstration uses a $CdSiP_2$-based device (CSP) that amplifies a 1-ps, 0.7-nJ, 3.4-µm seed pulse to 42 µJ using a 1-ps, 95-µJ, 2.2-µm pump pulse with Gaussian spatiotemporal intensity profile. Pump (orange) and signal (blue) beams are combined in a Rochon prism (RP) and made collinear at the CSP crystal (Fig. 2a), where the OPA+SHG process amplifies the signal while producing a 3.1 µm idler SH (purple) and residual 6.2 µm idler (green). Reflections of the beams from a CaF_2 beam sampler (BS) are imaged in a 2F configuration to a bolometer camera and separated by polarization using a Wollaston prism (WP). The inset of Fig. 2b shows the depleted pump and signal beam profiles at full pump input power. Fig. 2c shows the first ever observation of the OPA+SHG dynamics that lead to a modulated ring pattern across the pump spatial profile as its cyclic exchange of energy with the signal and idler is damped out at successively larger radial coordinates. For amplifier efficiency (Fig 2b), the beam sampler is removed, and a bandpass filter (BP) is used to isolate the signal. The transmission of the AR-coated CSP (96% on each facet) and bandpass filter (79%) were measured to back-calculate the internal efficiency of the device as plotted in Fig. 2b. 44% conversion efficiency (68% pump depletion efficiency) is observed at full pump power. Further conversion appears to be limited by spatial walk-off.

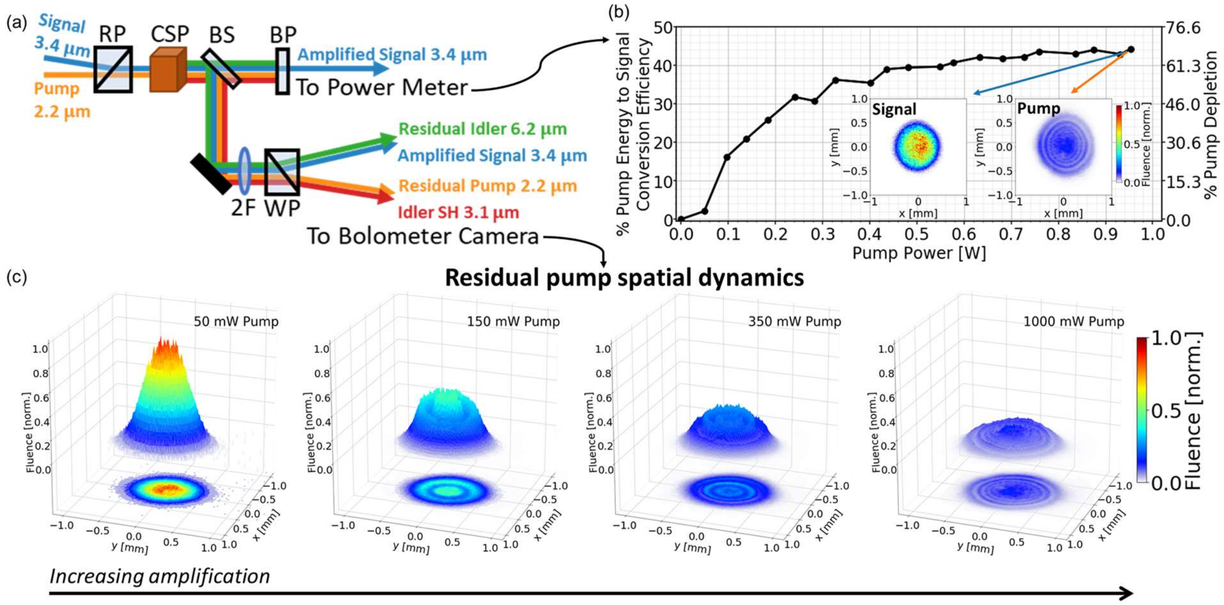

Fig. 2. (a) Experimental setup showing amplification in a CSP crystal and subsequent separation for measurement. (b) Signal efficiency as a function of pump power showing saturation at 44% signal conversion corresponding to 68% pump depletion. c) Pump spatial profile verifying the predicted damped oscillatory OPA+SHG dynamics.

While this experiment used collinear beams and birefringent phase matching, established techniques such as quasi-phase matching [6] and noncollinear geometries [7] can be used to provide a wide frequency tuning range in crystals such as BBO and $LiNbO_3$ for near-IR and CSP for mid-IR. Noncollinear devices in particular are a route towards tunable and efficient downconversion of high average power 1- and 2-µm solid-state diode-pumped lasers. An additional advantage of this technique is that the energy preserved in the idler SH can be reused to further pump the signal, possibly allowing two-stage conversion efficiency exceeding the one-stage quantum defect. Finally, while this first demonstration uses 1-ps signal pulses, several combinations of materials, parameters, and techniques are under study to scale this process to few-cycle durations.

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