Second Harmonic Amplification

Noah Flemens, Nicolas Swenson, and Jeffrey Moses
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA.
nrf33@cornell.edu

ABSTRACT: Hybridized OPA and idler SHG suppresses back-conversion in OPA, dramatically improving efficiency. Spatiotemporal analysis of CSP and LNB-based devices demonstrates up to 55% energy conversion to signal and efficient fractional harmonic pump upconversion.

The efficiency of optical parametric amplification (OPA) is fundamentally limited by asynchronous spatiotemporal conversion due to the local dependence of conversion-back-conversion cycles on the field intensity. For Gaussian-like beams, the pump photon depletion efficiency is typically 10-30% with only 5-15% of the pump energy going to the signal. Improving this efficiency would dramatically lower 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, damage threshold, and cost of pulse shaping poses a severe limitation. A recent technique of "quasi-parametric amplification" demonstrated a significantly boosted conversion efficiency using a carefully chosen material and dopant concentration to induce linear absorption at the idler wavelength, thus suppressing back-conversion [5].

Here we introduce and demonstrate a new fully parametric approach of idler mediated second harmonic amplification (SHA), a hybrid nonlinear process of second harmonic generation (SHG) and OPA, where SHG at the idler wavelength is phase matched to suppress back-conversion to the pump (Fig. 1a,d). We find the nonlinear system universally converges to full pump depletion for initial field conditions pertaining to an OPA. This solves the OPA spatiotemporal inefficiency problem. Using a spatiotemporal numerical analysis, we demonstrate a highly efficient OPA device based on $CdSiP_2$ (CSP) that converts a 1-ps, 2.05-μm pump laser with Gaussian spatiotemporal intensity profile to 3.0 μm with 80% pump photon depletion and 55% pump to signal energy conversion efficiency. We also demonstrate efficient idler second harmonic (SH) generation – thus enabling the application of efficient fractional harmonic upconversion of the pump – in a superlattice lithium niobate (LNB) based quasi-phase matching (QPM) device that upconverts a 1-ps, 1.03-μm laser with Gaussian spatiotemporal intensity profile to 0.85 μm with 27% pump to idler SH energy efficiency, a dramatic improvement compared to cascaded OPA and SHG stages.

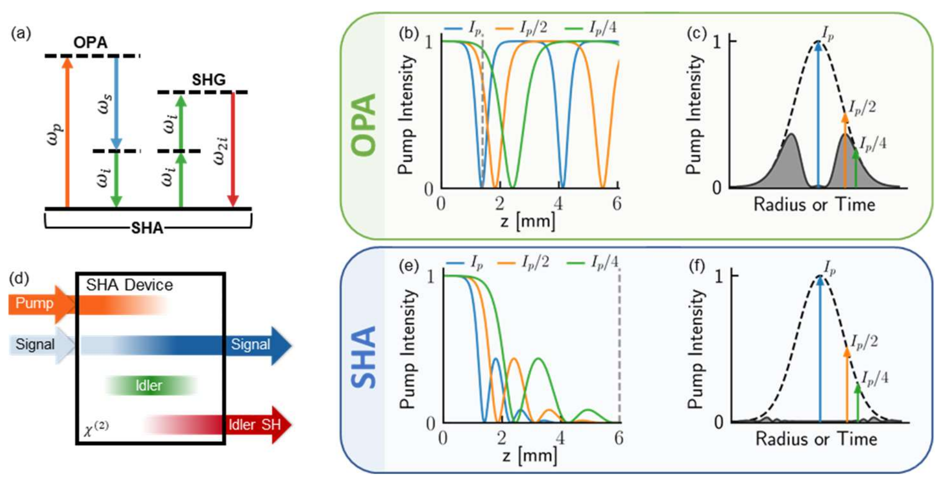

Figure 1. (a) SHA photon exchange diagram. (b) Conventional OPA dynamics at 1, ½, and ¼, of the pump peak intensity, which displays the inhomogeneity responsible for low OPA conversion efficiency. The gray dashed line represents the optimal conversion length where (c) represents a slice of the pump intensity profile along a transverse coordinate at this position, illustrating limited conversion efficiency. (d) A schematic of the SHA conversion device. (e) SHA dynamics as in (b) but with simultaneous phase matching of SHG at the idler wavelength. There is now a common length for full pump depletion (gray dashed line). (f) represents a slice of the pump intensity profile at this position.

The SHA process is described by four coupled wave equations:

$$dA_s/dz = i\kappa_s A_p A_i^* e^{i\Delta k_{OPA} z} \ (1), \quad dA_p/dz = i\kappa_p A_s A_i e^{-i\Delta k_{OPA} z} \ (2),$$

$$dA_i/dz = i\kappa_{i,OPA} A_p A_s^* e^{i\Delta k_{OPA} z} - i\kappa_{i,SHG} A_{2i} A_i^* e^{i\Delta k_{SHG} z} \; (3), \quad dA_{2i}/dz = -i\kappa_{2i} A_i^2 e^{-i\Delta k_{SHG} z} \; (4),$$

where κ_j, and A_j are the electric field coupling constants, and amplitudes, respectively, for signal (s), pump (p), idler (i), and idler second harmonic (2i). The OPA and SHG phase mismatch are given by $\Delta k_{OPA} = k_p - k_s - k_i$ and $\Delta k_{SHG} = k_{2i} - 2k_i$. Numerical integration of these equations when $\Delta k_{OPA} = 0$ and $|\Delta k_{SHG}| \gg 0$ shows the dynamics of an ordinary OPA (Fig. 1b). Fig. 1c depicts the optimal pump depletion profile along one transverse coordinate (time or space). Integrated over two transverse spatial dimensions and time, the overall pump depletion is only ~20%. In contrast, when $\Delta k_{OPA} = \Delta k_{SHG} = 0$ (Fig. 1e), the dynamics initially proceed as an OPA with the first term of Eq. 3 acting as ordinary OPA gain on the idler. However, when the pump nears full depletion, the second term of Eq. 3 – a loss term due to SHG – becomes comparable in magnitude to the first. This leads to damped conversion-back-conversion cycles and a >90% three-dimensional integrated pump depletion, making efficient OPA possible.

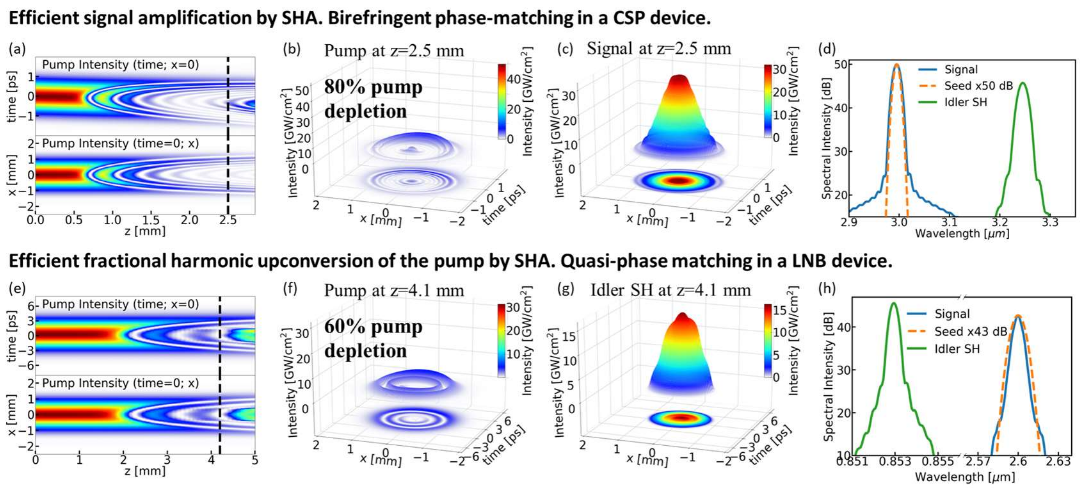

Figure 2. SHA makes possible both pump-to-signal amplification and pump frequency upconversion. (a,e) Pump depletion dynamics in SHA for slices along the pump spatiotemporal intensity profile. (b,f) Residual pump spatiotemporal profile after 80% (60%) depletion and (c,g) signal (idler SH) profile containing 55% (27%) of the original pump energy. (d,h) Signal and idler SH spectral intensities.

We present a full spatiotemporal simulation of high-gain SHA achieved by simultaneous birefringent phase matching of OPA and SHG in a bulk CSP crystal at 44.8° for a 2.05 μm, 2.5 mJ, 1 ps pump and a 3 μm, 1 μJ, 1 ps signal, all Gaussian. The damped conversion cycles of the pump can be seen in Fig. 2a across both the transverse spatial and temporal domains. Fig. 2b,c shows the output profile of the pump and signal, respectively, for a device cut at 2.5 mm. 80% of the pump energy is depleted with 55% going to the signal. In comparison, when $|\Delta k_{SHG}| \gg 0$ (i.e., conventional OPA) only 14% of the pump energy is depleted with 9% going to the signal at the optimal crystal length. The output signal and idler SH spectra are shown in Fig. 2d.

SHA can also be phase matched by means of a superlattice QPM device in LNB. This is achieved by creating a device poled at two frequencies $G_{+,-} = \Delta k_{OPA} \pm \Delta k_{SHG}$ in superposition. With the flexibility of QPM, SHA offers a potential monolithic and efficient route to fractional harmonic upconversion of the pump frequency, since $\omega_p < \omega_{2i} < 2\omega_p$ when $\omega_i > \omega_s$. We modeled a superlattice QPM LNB device for a 4.8 ps, 2.4 mJ, 30 GW/cm^2 chirped pump pulse at 1.03μm and a 5 ps, 50 nJ chirped seed pulse at 2.6 μm, each with 1-ps TL duration. 60% pump depletion was obtained after 4.1 mm of propagation (Fig. 2e,f) with 27% energy upconversion to a 0.85 μm idler SH (Fig. g,h), a dramatic improvement over the upconversion efficiency achieved when cascading OPA and SHG stages.

We find SHA to be broadly applicable to OPA and upconversion implementations by collinear or noncollinear birefringent phase matching or by QPM. Experimental data for the CSP device is currently being collected.

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