Energy scaling of hollow-fiber frequency conversion of ultrafast pulses

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Support: CSM, NSF
Gas as nonlinear medium:
- low dispersion
- supports high intensity
- third-order mixing

Use capillary to guide pump beams:
- increase interaction length
- Phase-matching of conversion:
  tune pressure to balance gas/waveguide phase

\[ \omega_{\text{signal}} = 2 \times \omega_{\text{pump}} - \omega_{\text{idler}} \]

Earlier mixing results:

- Pressure optimum produces lowest-order HE_{11} UV mode
- XPM can broaden bandwidth
- Compress to 8fs
- High conversion efficiency (40% from pump)
- Output energy in the 1-5\,\mu J range

Energy limitations: ionization, cross phase modulation
**OP-CPA:** optical parametric chirped pulse amplification

**Stretch pulse:** same intensity, more energy

\[ \omega_{\text{signal}} = 2 \times \omega_{\text{pump}} - \omega_{\text{idler}} \]
OP-CPA: conversion simulations

Saturated conversion without gain-narrowing is possible

- Low gain for seed → low degree of gain narrowing
- Wide-band or narrow-band pump
- Third-order process → generate new wavelengths
- High output beam quality: single mode
- But requires high input beam quality for efficient waveguide coupling
- Output spectrum is not narrowed

Shown here: 4ps pump, 1.8mJ 50% conversion to UV
# Comparison of amplifier technologies

<table>
<thead>
<tr>
<th></th>
<th>Laser crystal amplifiers</th>
<th>OP-CPA (crystals)</th>
<th>OP-CPA (hollow fiber)</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy storage</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>ASE/prepulses</td>
<td>✓</td>
<td>x</td>
<td>x</td>
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<tr>
<td>gain-narrowing</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
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<tr>
<td>thermal loading</td>
<td>✓</td>
<td>little</td>
<td>x</td>
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<tr>
<td>dispersion</td>
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<td>little</td>
<td>x</td>
</tr>
<tr>
<td>B-integral</td>
<td>some</td>
<td>little</td>
<td>little</td>
</tr>
<tr>
<td>amp λ</td>
<td>limited choice</td>
<td>$\lambda_a &gt; 400$</td>
<td>$\lambda_a &gt; 100$</td>
</tr>
</tbody>
</table>

## Pump req’ts

<table>
<thead>
<tr>
<th></th>
<th>limited choice</th>
<th>$\lambda_p &gt; 355$</th>
<th>$\lambda_p &gt; 200$</th>
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</thead>
<tbody>
<tr>
<td>pump λ</td>
<td>limited choice</td>
<td>$\lambda_p &gt; 355$</td>
<td>$\lambda_p &gt; 200$</td>
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<tr>
<td>duration range</td>
<td>wide</td>
<td>&lt;1ns</td>
<td>&lt;100ps</td>
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<tr>
<td>shape</td>
<td>any</td>
<td>flat-top</td>
<td>gauss, flat</td>
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<tr>
<td>beam quality</td>
<td>gauss-flat</td>
<td>flat</td>
<td>gauss</td>
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<tr>
<td>alignment</td>
<td>easy</td>
<td>overlap, angle</td>
<td>mode-matching</td>
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<tr>
<td>bandwidth/phase</td>
<td>any</td>
<td>narrow</td>
<td>narrow or chirped</td>
</tr>
</tbody>
</table>
Hollow fiber OP-CPA: experiment

Physics Department

Colorado School of Mines

Input:
820nm, 30fs
1.8 mJ, 10 Hz

• dispersion compensation: short pulse IR into BBO and into capillary
• additional dispersion to blue
• control duration of IR w/add’l material

BBO (0.5mm)

0.25” BK7

Capillary (150μm x 30cm)
Energy extraction

Without saturation, UV output should decrease with greater IR duration:

• signal is linear in IR

With saturation, UV yield increases with IR duration:

• longer IR seed can sweep out more of pump pulse energy
• cross-phase modulation is greatly reduced
Energy conversion: experimental results

**Input:** blue 110 fs, 48μJ  IR: 40μJ

**Output increases with IR chirp:**
- better overlap/extraction
- less XPM
- measure 20μJ depletion of blue (may not be seeing all of UV)
- limited by focusability of blue at high conversion
Dispersion-free SD-FROG

Three-mirror self-diffraction FROG:
• simple setup/alignment
• only reflections: wide bandwidth/dispersion-free
• less than 1 μJ input required

Doubling at high conversion efficiency is easy...
  • even with “thick” crystals, conversion gives short pulse
  • conversion saturates in first layer of crystal

... but preserving beam quality is not.
  • At high conversion (~50%) focusing quality deteriorates
Further scaling: opposite chirp mixing

10 Hz
800 nm
20 fs Pulse
Ti:Sapphire
CPA System

0.5 mm BBO

~30% Conversion to 400 nm

4 cm BK7

2.6 mrad

1/2

Opposite-chirp mixing for blue → ~50% more output (14.5μJ)
OP-CPA: compression simulations

UV output has negative chirp (even orders of IR phase change sign)

Compressed UV output as short as original IR pulse (chirped pump gives shorter output)

Prism pair: +’ve dispersion mode (correct sign of 2nd and 3rd order phase)
Future prospects: energy/wavelength scaling

**Scaling to higher energy:**
- higher-energy amplifier
- improve focusability of blue
- current:
- scale to TW level:

```
Pump 100fs, 50μJ  ->  UV 12μJ (25%)
```

```
Pump 170ps, 80mJ  ->  UV 20mJ (25%)
```

**Scaling to short wavelength for high-power VUV:**
- pump pulse can be narrow-band
- mix 800nm with: YAG harmonics:
  - 355nm → 230nm, 266nm → 160nm, 210nm → 120nm
Applications of high-power UV pulses

- pump for recombination XRL
- tunneling ionization in high-frequency limit
- micromachining - materials processing
- hard x-ray generation
- efficient low-order HHG
- photoelectron spectroscopy: fast dynamics of small molecules
Mixing simulations

Propagation code calculates saturated conversion

Input fields:
• energy, pulse duration, chirp, relative delay

Pressure loop
Propagation step loop: split-step + Runge-Kutta

Time domain:
• spm, xpm
• nonlinear mixing

Frequency domain:
• dispersion, losses

Output processing:
• energy calculation
• post-compression

Major assumptions:
• discrete-mode propagation
• five harmonic fields
• no bending losses
• no ionization
Characterization of input pulses

Blue pulse:
- initially 35fs
- chirped to 110fs with 8.5mm BK7, 3mm fused silica

IR pulse:
- initially 45 fs
- chirped to 51, 57, 63fs with additional BK7
Compression

UV pulse compression:
- positive IR chirp gives negative UV chirp
- simple compression with material not sufficient: 3rd order
- even orders of phase change sign, odd remain same

adj prism insertion

- prisms in positive dispersion allow 2nd and 3rd order compensation
- characterize with SD FROG

Group delay for FS prism pair (10cm sep)
Molectron J3-05 Joule-Meter

800 nm
400 nm

Capillary Cell
ID 120 m, length 63 cm
86 Torr Argon

f=500 mm
f=750 mm

20.7-J UV