Linear and nonlinear shaping of ultrashort optical pulses.

Alessandro Averchi

CNISM and Department of Physics and Mathematics, Università dell’Insubria, Via Valleggio 11, IT-22100 Como, Italy.
Ultrafast Optics

- **Study of optical phenomena on a sub-picosecond scale (<1ps)**
  - 1 ps = $10^{-12}$ s ; 1 fs = $10^{-15}$ s; 1 as = $10^{-18}$ s
  - Commercial systems: 25fs

- **High power pulses:**
  - es. Laser “Twinkle”, 1 ps, $P > 1$ GW, $E=8mJ$
  - Laser “Trident” 50 fs, $E=10$ mJ

- **Linear Optics:**
  $$P(t,x,y,z) = \varepsilon_0 \chi(t,x,y,z) |E(t,x,y,z)|$$

- **Nonlinear optics:**
  $$|P(t,x,y,z)| = f(|E(t,x,y,z)|)$$

- “Secondary” ultrashort sources
Generation of coherent, broadband e.m. radiation

- Ultrabroadband sources

- THz: 100 um < λ < 1mm

- HHG: <100 nm

Attophysics
Outline: nonlinear and linear pulse shaping

**NL**
- Spontaneous formation of X-waves in filamentation in air
- Tunable, octave-spanning supercontinuum driven by X-Waves formation;
- X-waves generation via Cross-Phase modulation in Kerr media;
- Spontaneous Bessel beam formation in two photon absorption regime;

**L**
- “Reflexicon”: All-reflective system for Bessel beam generation from intense, ultrashort pulses (HHG experiment);
- Tailoring of optical pulse filamentation for broadband Terahertz emission;
X-Waves: Wavepackets achieving stationary propagation in a medium.

- “X” shape in the direct \((r,t)\) and inverse \((\theta, \lambda)\) or \((k_\perp, \omega)\) space.
  - Polychromatic, coherent superposition of Bessel Beams (non-diffracting).
  - Angular Dispersion compensate material dispersion (non-dispersive).

- Formed in different systems:
  - Acoustic Waves, X(2) Materials, Waveguide Arrays, Photonic crystals, Laser Cavities...
  - Filamentation in Kerr media (liquids, solids, air?)

In \((k_\perp, \omega)\) space the X-wave relation is given by:

\[
k_z(\omega) = k(\omega_0) + \frac{\omega - \omega_0}{v_X}
\]

- \(v_X\): group velocity of the X-wave.
- \(\omega_0\): central frequency
Optical pulse filamentation in Kerr media

- **Kerr:**
  - intensity-dependent refractive index:
    \[ \overline{P} = \varepsilon_0 \left( \chi E + \chi^{(3)} |E| E \right) \]
    
    \[ n_{\text{tot}} = n_0 + n_2 I(t, x, y, z) \]
    
    H2O, Silica, Air, Noble gases...
    
    - Self Focusing
    - Self Phase Modulation

- **Filamentation:** non-diffracting, high intensity peak for distances >> Rayleigh range

  \[ I_{\text{peak}} : \text{TW/cm}^2 \]

  plasma, white light continuum, conical emission...
Filamentation in Air: what is a “filament”? 

Fs Laser source, 35 fs, 30 mJ energy 
IESL-FORTH, Heraklion
Spontaneous **reshaping** into an X-wave

- Clearly observed in the inverse space \((\theta, \lambda)\) with an imaging spectrometer;
- Long focal lens (10m) needed;
- First time in air;

Conical Emission - Spatial far-field \((x, y)\)
Non-diffractive propagation

- $I > 10^{13}$ W/cm². How can we measure the beam width?
- Has been interpreted as a balancement between Kerr (focusing) and plasma (defocusing)
- Continues after the end of the plasma string -> X-wave

Burnt Spots on photographic paper, scanned with 16bit scanner and analyzed
- Characterization of energy flux (conical) - Antonio

Published in Optics Express Vol.16 -1565 (2008)
Tunable, octave-spanning supercontinuum driven by X-Waves formation in condensed media.

- Wide broadening of the pulse spectrum during propagation (SPM);

- Recent observations of unexpected spectrally isolated blue-shifted emission.

- Our Experiment:
  - Fused Silica in Normal Dispersion regime;
  - Generation of a spectrally isolated blue peak;
  - SC with an octave span from the pump pulse;
  - Tunable in a range of 150 nm;
  - X-Waves formation in filaments;
Experimental Setup.

- 1.2 ps, $\lambda_0=1055$ nm pulse

- Focused with a lens $f=51$ cm in a fused silica sample, Length= 2 cm.

Two diagnostics:
- Fiber spectrometer: radially integrated spectrum;
- Imaging spectrometer + Camera: angularly resolved spectrum $(\theta, \lambda)$;
At threshold for Filamentation a Spectrally Isolated peak appears in the blue.

- Central wavelength: 450nm.
  More than an octave separation from the pump.
- Energy in the blue peak: \(~ 100\text{nJ}\).

- At higher energy octave spanning supercontinuum.
- SC broadening starts from the blue, not from the central wavelength of the pulse.
Measurements in the \((\theta,\lambda)\) spectrum reveal the X-wave reshaping of the pulse.

- Conical Emission around the pump pulse: X-Wave forming.
- The blue peak is itself conical.
- The X-wave relation matches the
  \[
  k_z(\omega) = k(\omega_0) + \frac{\omega - \omega_0}{v_X}
  \]
  \(v_X\): group velocity of the X-wave. Derived by the experimental angular spectrum around 1055 nm
- Blue peak and pump belong to the same physical object: the X-wave.
The wavelength of the blue peak is determined by group velocity of the X-wave.

- **X-wave relation:**

\[ k_z(\omega) = k(\omega_0) + \frac{\omega - \omega_0}{v_X} \]

- **Phase matching condition:**

\[ \Delta k(\lambda) = k(\lambda) - k_{x-wave}(\lambda) \]

- **Only** \( \lambda = 450 \text{ nm} \) **is phase-matched on axis**

- **Explains why the isolated blue peak appears first.**

The input pulse undergoes pulse splitting: \( V_g \) is different from the \( V_g \) of the input pulse.
The spectral position of the blue peak is tunable in a 150 nm range.

- Changing the velocity of the splitting pulses: the X-wave phase matching conditions are different.
- Depends on intensity at nonlinear focus.
- Done by changing the sample position around the focus of the input lens.

\[ z = 49, 50, 51, 52.5, 53, 54 \text{ cm} \]

\[ \text{Lens focal length} = 51 \text{ cm} \]

Other strategy: changing the input beam aperture with an iris.

“temporal” shaping with “spatial” method
- Oral presentation at Ultrafast Phenomena - Stresa, June 2008

- Published in Phys. Rev A 78, 033825

- Used as seed pulse in a further experiment (Matteo)
Generation of X-waves by Cross phase modulation

- two copropagating pulses: strong (pump) -filament- and weak gaussian seed at a different wavelength

coupled equations:

\[
\begin{align*}
  j \frac{\partial A_P}{\partial z} &+ \frac{1}{2k_0} \nabla_\perp^2 A_P - \frac{k''}{2} \frac{\partial^2 A_P}{\partial \tau^2} + k_0 \frac{n_2}{n_0} [|A_P|^2 A_P] = 0 \\
  j \frac{\partial A_S}{\partial z} &+ \frac{1}{2k_0} \nabla_\perp^2 A_S - \frac{k''}{2} \frac{\partial^2 A_S}{\partial \tau^2} + k_0 \frac{n_2}{n_0} [2|A_P|^2 A_S] = 0
\end{align*}
\]

Cross phase modulation

localized \((r,t)\) change in the refractive index

\[\Delta n(r,t) = 2n_2 I_p(r,t)\]
XPM acts as a “spatiotemporal lens”

- Deforms the phases of the seed pulse
- No energy transfer from pump to seed
- Highly localized \((r,t)\) pump pulse and a wide seed

\[ \Delta n(r,t) \]

- In a dispersive medium seed and pump travels at a different GV
Traveling source of polarization $\Delta n$

How is the seed reshaped along propagation?
XPM as a scattering process (PRL Kolesik et. al. 92 253901)

- Seed approximated as a plane wave (infinite, monochromatic $\omega_0$)
- Localized Polarization peak induced by NL propagation of the pump: scatterer moving at $V_g$ of the pump.

Longit. momentum matching:

$$k_{z,s} = k_{z,in} + \frac{\Omega}{v_{g,p}}$$

$\Omega = \omega - \omega_0$
XPM reshapes the seed into an X-wave

\[ k_{z,s} = k_{z,in} + \frac{\Omega}{v_{g,p}} \quad \text{\(k_z\) linear in \(\omega\)}

constant \(V_g\) on axis:

\[ V_{gz} = \left( \frac{\partial k_z}{\partial \omega} \right)^{-1} = \left( \frac{1}{v_{g,p}} \right)^{-1} = v_{g,p} \]

- The scattered seed propagates without GVD thanks to angular dispersion: X-wave
- Same group velocity as the pump
Experimental setup

Filament energy: 20 $\mu$J
Seed energy: 5 nJ - 1 $\mu$J
No energy transfer
Fit with X-wave (scattering) relation using filament $V_g$:

$V_g = 2.22 \times 10^8 \text{ m/s}$

$V_{g527} = 2.02 \times 10^8 \text{ m/s}$
Near field - output facet of the sample

- Filament FILTERED OUT in both images

Radial profile

fit with function: \( \frac{1}{br^2 + cr} \)

in agreement with \( 1/r^2 \) decay from theory
Non diffractive propagation (linear)

- Imaging scanning along z after the end of the sample
- Propagation of the X-wave is no more non-dispersive but is still non-diffractive over 5 mm

a Gaussian with same init. diameter would spread 15x
Bessel beam pump

- LASER: Ti:Sapph, 35 fs, 800 nm. Bessel Pump energy: 1 mJ, chirped pulse 1 ps FWHM
• Presented at SIAM conference on Nonlinear waves (NW08) - Rome, July 2008

• Accepted for publication in Optics Letters
Spontaneous Bessel reshaping in TPA regime

- Nonlinear losses: multiphoton absorption processes of order $K$ ($K=\text{number of photons}$);
- Usually $K>2$ in filamentation -> spatiotemporal reshaping, X-waves;
- In Two Photon Absorption (TPA) regime the spontaneous dynamic is different: Bessel reshaping

Silicon 1550 nm; Silica 264 nm

Published in Opt.Expr - Matteo.

Symlified system: 1d NLSE equation + NLL

http://193.206.161.215/cgi-bin/pyNLSE.cgi
High Harmonic generation

- Interaction between intense laser pulse ($I > 10^{13} \text{ W/cm}^2$) and atomic gas (Argon, Neon, Xenon).
- **Non perturbative regime**: laser pulse field comparable to atomic field: tunneling.
- Harmonic order up to $100^\circ$
Phase Matching with Pulsed Bessel Beams (PBBs)

- Tunable axial wavevector:
  \[ k_z = k_0 - \beta \]

- By reshaping the pulse into a PBB with the proper angle we get Phase matching -> Increased efficiency by a factor 1000

- Published theoretical paper (Phys. rev. A)
Towards the experiment at ICFO

Setup Scheme

1. Reflective Bessel Gen.
2. Vacuum Chamber
3. Ar Gas injected in 2.
4. Rotary pump.
5. Diamond pin-hole
6. X-Y translator connected with 5.
7. Connecting tube
8. Teflon pinhole
9. Turbomol. pump (10^-2 mbar)
10. Vacuum Chamber
11. Turbomol. pump (10^-6 mbar)
12. Transmission Grating
13. XUV Camera
“Reflexicon” = Reflective axicon

- experimental conditions: $I > 10^{12}$ W/cm$^2$ and pulse duration = 25 fs;
- Standard Axicon: glass. Risk of damaging and of nonlinear effects inside the optical element
- Conical mirrors

Optical design -> Custom made elements
Terahertz emission from tailored filaments in air

- Thz emission measured in “two color” filaments, due to plasma and four wave mixing
- Combinations of converging lens + axicon (linear shaping)
THz pulse from optimized plasma

- Full electric field measured
- Duration 250fs, ca. half of the conventional system.
- Energy 100 nJ
- Increased Spectral bandwidth (good for applications)
- Tough part of the job: THz collection and detection

Paper in preparation
Publications, presentations & schools


• Ultrafast phenomena, Stresa - June 2008
• SIAM conference on Nonlinear Waves, Rome - July 2008

• STELLA School, Heraklion, April 2008
• “Discrete optics and beyond”, Bad Honnef, May 2008