Nonlinear spatio-temporal dynamics in microstructured fibers

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Nonlinear Spatiotemporal Photonics

spatial

(discrete) diffraction, competition of multiple modes

spatial solitons, filamentation, vorticies, Anderson localization

nonlinear, disordered

$\chi^{(2)}, \chi^{(3)}$, cascaded, noninstantaneous, or otherwise complex

supercontinua, rogues waves

temporal

dispersion (all orders), (spectral) loss, noninstantaneous response

superluminal pulses, linear non-diffracting waves

?
Nonlinear Spatiotemporal Photonics Challenges & Methods

- waveguide arrays
- fibre arrays
- continuous media

- Light Bullets (properties, excitation & decay)
- direct spacetime coupling
- vortex Light Bullets

- pulse shaping
- multispectral analysis
- imaging X correlation
- imaging XFROG

- semi-analytic, simplified models
- complete, parallel spatiotemporal solvers

suitable environments

experimental techniques

effects & interaction

theoretical methods
Fibre Arrays – 2D Nonlinear System

- temporal dynamics in fibres well understood → array of fibre cores
- exploit Photonic Crystal Fibre technologies and high quality materials

Ballistic transport for homogeneous system
Fibre Arrays – 2D Nonlinear System

→ extreme regularity

stack → draw → final result

Linear Properties of Fibre Arrays

- experimental discrete diffraction pattern

- discrete diffractions is strongly wavelength depended

- **dispersion of coupling**
  → non-instantaneous diffraction
  → **direct space-time coupling**

\[
-i \frac{\partial A_{nm}(z,t)}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 A_{nm}}{\partial t^2} + \gamma |A_{nm}|^2 A_{nm} + \left(c_0 + ic_1 \frac{\partial}{\partial t}\right)(A_{n+1m} + \ldots + A_{n-1m-1})
\]
A short pulse of light is focused into a sample…

… and is broadened by dispersion and diffraction.
Can nonlinearity arrest this broadening?

- spatiotemporal, solitary, non-dispersive/non-diffractive wave packet of finite energy is called Light Bullet (LB)
- dynamic properties:  
  - collapse in homogeneous system  
  - stable in discrete system!
• launch 170 fs pulse into fibre array, increase power, look for LB
• observe some spatial contraction
• **no temporal contraction** observed
  - no autocorrelation contrast
  - **white light** instead
similar results by other groups
Eisenberg et al., PRL 87, 43902 (2001)
Cheskis et al., PRL 91, 223901 (2003)

Which parts of the PHYSICS are really important?
Identification of Spatiotemporal Parameter Regimes

- LBs very short (a few fs) → higher order effects influential
- Mismatch between laser and LB → supercontinuum
  → spatiotemporal analysis-scheme needed for separation
- Complex dynamics → sophisticated analysis
• unidirectional Maxwell equation for amplitude $E_{nm}(t)$ in $n^{th}$ waveguide

$$-i \text{sgn}(\omega) \frac{\partial}{\partial z} E_{nm}(z, \omega) = \left[ \beta(\omega) - \omega \beta_1(\omega_0) \right] E_{nm}(z, \omega) + c(\omega) \sum_{n'm'} C_{nm}^{n'm'} E_{n'm'}(z, \omega)$$

$$+ \frac{4}{3} \gamma P_{nm}^{NL}(z, \omega)$$

$$P_{nm}^{NL}(z,t) = E_{nm}(z,t) \left[ (1-f) E_{nm}(z,t)^2 + f \int E_{nm}(z,t-t')^2 h(t') dt' \right]$$

$$h(t) = \begin{cases} 0 & t < 0 \\ \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2} \exp(-t/\tau_2) \sin(t/\tau_1) & t \geq 0 \end{cases}$$

• includes: dispersion to all orders, wavelength dependent coupling, delayed Raman-response

• no SVEA $\rightarrow$ carrier wave dynamics!

• parallel solver; but not slower than SVEA codes

Kolesik et al., PRE 70, 036604 (2004); Benton et al., PRA 78, 033818 (2008); Babushkin et al., Opt. Exp. 15, 11978 (2007); Kinsler, PRA 81, 023808 (2010)
Experimental short pulse characterization

How to measure spatiotemporal, ultrashort pulses?

spatial: imaging lens + camera

compatible (SF preserves phase)

temporal: sum-frequency cross correlator

imaging cross correlator
Imaging cross-correlation FROG ➔ iXFROG

Retrieval of ultrashort, complex, spatiotemporal fields
Experimental Overview

- excite with ultrashort pulses
- analyze with spatiotemporal imaging cross-correlator
Imaging Cross Correlator - Setup

- Reference pulse (short and wide)
- Pulse from experiment (signal)
- Thin BBO crystal (sum-frequency)
- Delay line ($\tau$)
- Imaging lens
- Sum-frequency field
- CCD camera
• example: nonlinear pulse propagation in a fiber array

Goals:
• measure phase
• improve time resolution (10 fs)
• „plug-in“ architecture
some candidates for ultrashort pulse retrieval

• SPIDER [1]
  • fairly complex setup
  • difficult to implement with imaging scheme
  • no „plugin“ to cross-correlator
  • needs reference at signal wavelength
  • reference spectrum must be broader than signal
• SHG-FROG [4]
  • possible, but not necessary (we have a reference)
  • in general not so sensitive
• XFROG [5]
  • compatible with imaging
  • makes use of cross-correlation setup
  • makes use of existence reference

• …many other possible techniques → XFROG just blends in with existing setup

iXFROG setup schematic

- Pulse from experiment (signal)
- Thin BBO crystal (sum-frequency)
- Delay line (τ)
- Sum-frequency field
- Spectrally filtered sum-frequency field
- Tunable wavelength filter
- Imaging lens
- CCD camera
Filter Requirements

- wavelengths: $\lambda_{\text{sig}} = 1550 \text{ nm}$ and $\lambda_{\text{ref}} = 800 \text{ nm} \rightarrow \lambda_{\text{SF}} = 527 \text{ nm}$

- Requirements on the Filter
  - resolution: 10 fs $\rightarrow$ $\sim 100 \text{ nm}$ free spectral range
  - range: 1000 fs $\rightarrow$ $\sim 1 \text{ nm}$ spectral resolution
  - angular independence $\rightarrow$ $\sim 4 \text{ deg}$
  - acceptable field diameter $\rightarrow$ $\sim 8 \text{ mm}$
  - tunability and stability
- solution: Fabry-Perot Interferometer (FPI) with tunable mirror separation
choose mirror properties to attain spectral resolution and free spectral range

\[ N_t = \frac{\Delta \lambda}{\delta \lambda} \approx 100 \]

- spatial resolution is limited by BBO diameter \( D \) and angular variation of the FPI transmission

\[ N_x = \frac{D}{\lambda_{SF}} \sqrt{\frac{2}{\Delta \lambda/\delta \lambda}} \approx 300 \]

- total spatiotemporal complexity is therefore

\[ N = N_x^2 N_t = \left( \frac{D}{\lambda_{SF}} \right)^2 \approx 10^7 \]
Wavelength Selective Element

FPI requirements

- $d \approx 5 \, \mu m$
- $\delta d \approx 10 \, nm$

high degree of parallelity

further requirements:
- temperature insensitivity
- long measurements (drift compensation)
- mechanical stability

- 3-axis piezo mount
- rigid design
- closed-loop operation
feedback loop optimizes

- spectral contrast $\rightarrow$ FPI parallellity
- coarse distance (FPI working order)
- fine distance (transmitted wavelength)
Measurement Procedure Overview

- **Space**
  - take camera picture
  - 30 ms / 2D data / 25 kSamples

- **Time**
  - sweep delay line
  - 20 s / 3D data / 16 MSamples

- **Wavelength**
  - sweep wavelength
  - 45 minutes / 4D data / 1.5 GSamples

- **iX FROG**
  - pixel-wise application of XFROG algorithm
  - hours / 3D data / 30 MSamples
iXFROG: a Case Study

signal
- 25 fs pulse
- massive spatiotemporal distortions (self-phase modulated spectrum, imaging aberrations)
- 27,000 fs$^3$ chirp superimposed by spectral pulse shaper

reference
- 50 fs pulse
- 500 fs$^2$ chirp due to optical elements

![Image of signal and reference pulses with cross-correlation results](image)
- sub 25 fs pulse features over > 1000 fs window resolved
- spectral features with < 3 nm bandwidth over 100 nm resolved
- 28,000 fs$^3$ chirp retrieved
Light Bullet

spatiotemporal, solitary, non-dispersive/non-diffractive wave packet of finite energy
Experimental Observation of Light Bullets

- clear spatiotemporal separation of dispersive underground and LB
- Light Bullet found
• investigate properties of wave packet in central waveguide
• compare to properties of perfect LB

stationary propagation of LB with continuous redshift and slowing down
• increasing energy threshold due to increased diffraction $\rightarrow$ decay

Eilenberger et al. PRA 84, 013836 (2011)
Vortex Light Bullet

Increase complexity by reduced excitation symmetry
Nonlinear, Self-confined Vortex Waves

spatial

continuous

vortex solitons in square lattices

vortex solitons in hexagonal lattices

spacetime

• numerically evaluate stability of simplified VLB solutions

Creating a Discrete Vortex: Idea

discrete phase plate before focus lens

match with array structure

generate vortex field in focus
Experimental Overview

- excite LBs with discrete phase plate
- analyze with spatiotemporal imaging cross-correlator

A diagram shows:

- OPA
- phase plate
- fiber array
- beam combiner
- delay line
- imaging lens
- BBO
- camera

Wave lengths shown:
- 800 nm
- 1550 nm
- 527 nm
• measure cross-correlation sweep for given sample and energy

• display data from central cores only
• 20 fs resolution, 10 fs timing jitter
• extract mutual delay and relative energy
Simulation Results

What to look for in an experiment:
- short sample:
  - synchronized linear waves at < 50 nJ
  - single LB at <250 nJ
  - temporal and energetic synchronization at 250-300 nJ
  - multiple LBs at > 300 nJ

- long sample
  - no VLBs (no temporal and energetic synchronization)

- VLBs propagation for ~2.5 dispersion lengths
- narrow range of energies (250-300 nJ)
- desynchronization into individual LBs for longer samples
Experimental Results: Short Sample

- Synchronized linear waves at < 50 nJ
- Single LB at < 250 nJ
- Temporal and energetic synchronization at 250-300 nJ
- Multiple LBs at < 300 nJ
Conclusions

- Nonlinear spatiotemporal photonics, exploits all possible degrees of freedom

- LBs are prominent examples of space-time entities, with novel dynamic properties

- Observation of Vortex LB

- iXFROG with tuneable wavelength filter