Temporal focussing of ultrafast pulses through an opaque scattering medium

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Outline

• Introduction

• Technique: Spatially and spectrally resolved interferometry (SSI)

• Temporal focusing of scattered pulses behind opaque media

• Conclusion
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• Random scattering of coherent light
  – Wavefront distorted by multiple scattering
  – No large-scale correlations remain
  – Multiple interferences → spatial ‘speckle pattern’
What about broadband scattered pulses in time domain?

- Scattering process dispersive
  - different speckle pattern for each independent spectral mode (overall image contrast reduced)
  - Spatio-spectral resolution required to study individual speckle fields

- Temporally stretched with characteristic Thouless time
  - Formation of ‘temporal speckle field’

- Active compensation with pulse shaper?
  - Form temporally recompressed pulse?
• **Spatial phase-shaping** of incident c.w. wavefront
  – Inverts scattering process to form spatial focus:

• **Temporal control** of scattered femtosecond pulse
  – Exploit space-time coupling in sample with *spatial shaping*:
  – Spatially localized temporal focussing with *spectral shaping*:
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Spectral interferometry (SI)

- Femtosecond pulses too short for direct measurement of complex $E$-field $E(\omega) = A(\omega) \exp [i\phi(\omega)]$
  - Detectors measure intensity $\sim |E(\omega)|^2$
  - Reveals no information about spectral phase $\phi(\omega)$

- SI allows interferometric measurement of phase relative to reference pulse [$\phi_r(\omega)$ known/assumed]

\[
S(\omega) = |A_s(\omega)e^{i\phi_s(\omega)} + A_r(\omega)e^{i[\phi_r(\omega) + \omega \tau]}|^2
= |A_s(\omega)|^2 + |A_r(\omega)|^2 + 2 |A_s(\omega)||A_r(\omega)| \cos[\phi_s(\omega) - \phi_r(\omega) - \omega \tau]
\]
A wasted dimension?

- Cameras are 2D detectors
- ‘Spare’ camera axis for spatial resolution of frequency
Spatially and spectrally resolved interferometry (SSI) - method

- Multiply scattering sample (microscope slides spin-coated in 60µm ZnO powder) at focus of oscillator (1nJ, 30fs @ 800nm)

- Output surface imaged onto 2D spectrometer and interfered with reference beam

- Retrieve (relative) speckle electric field $E(x, \omega), E(x,t)$

Spatially and spectrally resolved interferometry (SSI) - extraction

\[
S(x, \omega) = \left| A_s(x, \omega) e^{i\varphi_s(x, \omega)} + A_r(x, \omega) e^{i[\varphi_r(x, \omega) + \omega \tau + k_x x]} \right|^2 \\
= |A_s(x, \omega)|^2 + |A_r(x, \omega)|^2 + 2 |A_s(x, \omega)| |A_r(x, \omega)| \cos[\varphi_s(x, \omega) - \varphi_r(x, \omega) - \omega \tau - k_x x]
\]
Spectral measurements

- **Reconstruct spatio-spectral intensity and phase**
  - No large-scale spatial or spectral correlations
  - Autocorrelation function retrieves speckle grain size (50µm) and medium bandwidth (2.55 mrad/fs)
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Spatial resolution of spectral phase

- Phase correlations over extent of speckle grain only

- In contrast to many control experiments, spatial resolution essential (spatially averaged phase meaningless!)

- EXPERIMENT: Active control of speckle temporal field
Experiment: speckle phase compensation & temporal focussing

1. Add pulse shaper before sample
2. Measure $E(x, \omega)$ of sample via SSI
3. Choose spatial ‘slice’ $x_0$ + programme $\varphi(x_0, \omega)$ into shaper
4. Measure $E(x, \omega)$ again + look for temporal focussing at $x_0$
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Folded 4f line
640 pixels over 30nm
0.06nm resolution
23ps shaping window
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Temporal focussing - results

- Measure unshaped spatio-temporal speckle field $E(y,t)$
Temporal focussing - results

- Phase compensation → emergence of intense peak
  - Spatially localized to 30 µm
  - Temporally focussed to 59 fs
  - Contrast ratio of 15 relative to unshaped background
  - Temporal background halved
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• Fully characterize spatio-temporal speckle electric field

• Form temporal focus by pre-compensating for sample dispersion with spectral phase pulse-shaper
  – Compression to Fourier-limit duration
  – Spatial localization and control due to speckle correlations
  – Bridge gap with time-reversal experiments in acoustics/GHz-electromagnetic realms

• Future directions:
  – Fundamental studies of complex media
  – Apply ultrafast diagnostic techniques (nonlinear microscopy, time-resolved microscopy...) deep within/beyond biological tissue
Thank you!
Spatio-temporal field reconstruction

- Fourier transform of $E(\omega, y)$ yields time domain $E(t, y)$
  - Complex spatio-temporal structure revealed
  - Repeat for several sample positions (ensemble averaging)
  - Average temporal behaviour reveals exponential decay
  - Thouless times measured for range of samples: 840fs to 2.5ps