Simple High-Sensitivity Electro-Optic Sagnac Spectral Shearing Interferometry for Short Optical Pulse Characterization

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A simple electro-optic spectral shearing interferometer can characterize ultrashort pulses at nW average power.

- Electro-optic spectral shearing interferometry (EOSI) directly measures a short optical pulse by interference of two relatively sheared pulse replicas.
- EOSI is implemented in a Sagnac interferometer for real-time versatile temporal characterization of free-running laser sources.
- The demonstrated EOSI setup
  - measures pulses in real time at nW average power with simple off-the-shelf components
  - accommodates sources at a wide range of repetition rates and wavelengths
Spectral shearing interferometry is a simple, accurate, and direct pulse characterization technique.

<table>
<thead>
<tr>
<th>Spectral field</th>
<th>Pulse 1: spectral shift</th>
<th>Pulse 2: time delay</th>
<th>Interference phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_1(\omega) = \sqrt{S(\omega - \Omega)} \times \exp[i\phi(\omega - \Omega)]$</td>
<td>$E_2(\omega) = \sqrt{S(\omega)} \exp[i\omega \tau] \times \exp[i\phi(\omega)]$</td>
<td>$\phi(\omega) - \phi(\omega - \Omega) + \omega \tau \rightarrow \phi(\omega)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spectrum</th>
<th><img src="image1" alt="Spectrum Pulse 1" /> +(\Omega) <img src="image2" alt="Spectrum Pulse 2" /> <img src="image3" alt="Spectrum Interference" /> 2(\pi/\tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td><img src="image4" alt="Intensity Pulse 1" /> <img src="image5" alt="Intensity Pulse 2" /> <img src="image6" alt="Intensity Interference" /></td>
</tr>
</tbody>
</table>

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EOSI uses linear temporal phase modulation to induce a spectral shear for high-sensitivity pulse characterization.

<table>
<thead>
<tr>
<th>Theoretical proposal&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Phase modulator</th>
<th>OSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interferometer followed by sinusoidally driven phase modulator&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Phase modulator</td>
<td>OSA</td>
</tr>
<tr>
<td>Shear in each arm of an interferometer&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Phase modulator</td>
<td>OSA</td>
</tr>
</tbody>
</table>


The Sagnac EOSI generates a spectrally sheared replica of the test pulse

- Spectral shear by linear temporal phase modulation
- Polarization rotation by 90°
- Propagation into birefringent element polarized along fast axis
The Sagnac EOSI generates a reference pulse co-polarized with the sheared replica

- Propagation into birefringent element polarized along slow axis
- Polarization rotation by 90°
- No spectral shear (backward propagation polarized along the low electro-optic efficiency axis of the modulator)
The Sagnac EOSI has practical advantages over other spectral shearing interferometry implementations.

- Relative delay between interfering pulses set by birefringence
  - intrinsically stable
  - interferogram resolvable by low-cost low-resolution spectrometer
A large-amplitude 10 GHz phase modulation is synchronized to the test pulse

- Free-running laser operating at $f_{\text{laser}}$
  - $(20 \text{ MHz} < f_{\text{laser}} < 200 \text{ MHz})$
- 10-GHz reference locked to $f_{\text{Laser}}$ by phase-locked dielectric resonator oscillator (PDRO) and temporally delayed by voltage-controlled phase shifter
- 10-GHz modulation amplified to 28-V peak-to-peak
- Low $V_\pi$ phase modulator provides a 38 rad, 10 GHz phase modulation at 1053 nm (shear on single optical pulse is 190 GHz = 0.7 nm)
The temporal phase modulation is highly dependent on the propagation direction and polarization.

- Amplitude of temporal phase modulation at 1053 nm determined with a cw laser
  - 38-rad peak-to-peak modulation for shearing optical path
  - 1.5-rad peak-to-peak modulation for reference optical path
The Sagnac spectral shearing interferometer was assembled with off-the-shelf components.

- Delay between interfering pulses set to ~2 ps
- Synchronization and interferogram acquisition performed via USB
The Sagnac EOSI setup has been tested on a 1053-nm mode-locked laser.

- 76-MHz, 1053-nm Nd:phosphate modelocked laser characterization
  - 20-μW average power
  - 15-ms integration time
- Accurate characterization of pulses from ~FT-limit to ~10 ps by adding fibers
- Chromatic dispersion added by fibers agrees with linear prediction
The Sagnac EOSI has demonstrated real-time pulse characterization at 800 nm with nW average power*

- LiNbO$_3$ modulator optimized for 800 nm and lower $V_\pi$ leads to a 280 GHz single-sided shear (0.6 nm)
- Operation at 1 nW with 150 ms exposure time
- Consistent measurements of interferogram and phase, although instrument internal dispersion was not compensated for

*We thank Prof. R. Sobolewski and J. Zhang for the availability of their laser system.
Summary/Conclusions

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