Pulse Shaping with MIIPS

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Outline

• Pulse shaping introduction
• MIIPS
  – MATLAB Simulations
  – Actual implementation

Laser pulses can be defined in the time or frequency domains

• Electric field of pulse is equivalently defined in both
  – Time: \( E(t) = \mathcal{F}\{E(\omega)\} \)
  – Freq.: \( E(\omega) = \mathcal{F}\{E(t)\} \)
• Typical fourier transform properties apply
The spectral phase components determine the temporal structure of pulse

- Constructive and destructive interference determines temporal profile
- As pulse propagates through air and optics, dispersion affects the temporal structure

\[ \phi = \phi_0 + \phi_1 (\omega - \omega_0) + \frac{\phi_2}{2} (\omega - \omega_0)^2 + \frac{\phi_3}{6} (\omega - \omega_0)^3 + \ldots \]

2\(^{nd}\) Order Phase

3\(^{rd}\) Order Phase
There are many methods to measure the temporal profile of fs pulses.

- **FROG**
  - Split beam in two
  - Cross in SHG crystal and scan time delay
  - Phase retrieval problem

- **SPIDER**
  - Split beam in three
  - Chirp one pulse and cross three in SFG crystal

The 4-f shaper allows the adjustment of spectral phase components.

- Once you have measured the phase, a simple way to correct it, or apply any phase is the 4-f shaper
- Spectral components modulated in fourier plane by SLM

MIIPS allows for pulse characterization and shaping in a single 4-f device.

- Takes advantage of SHG sensitivity to phase profile of input pulse
  \[ \sigma^{(2)}(\omega) = \sqrt{|E_x(\omega)|^2|E_y(\omega)|^2} \exp\left(i\phi_x(\omega)\right) \exp\left(-i\phi_y(\omega)\right) \]
- Place SHG crystal and spectrometer anywhere downstream of 4-f shaper to measure and correct phase at the point
MIIPS leverages SHG's dependence on the spectral phase profile.
MIIPS leverages NL signals to measure the input pulse’s phase profile.

- Input phase is unknown
  \[ \phi \]

- Apply reference phase modulation with variable parameter, watch SHG
  \[ \varphi = A \sin(\gamma \omega - \delta) \]

- For each step in parameter variation, maximum SHG signal occurs when curvature of total phase is 0.
  \[ \phi'' + \varphi'' = 0 \]

- Construct 2nd derivative, double integrate to find phase
  \[ \varphi'' = \gamma^2 A \sin(\gamma \omega - \delta_m(\omega)) \]

- Apply inverse of phase to correct on SLM
  \[ \varphi = -\gamma^2 A \int \sin(\gamma \omega - \delta_m(\omega)) d\omega \]

MIIPS iterates on this procedure to find the correct phase to apply.

Apply reference phase on top of unknown phase, scan the \( \delta \) parameter.

\[ \varphi = A \sin(\gamma \omega - \delta) \]

MIIPS iterates on this procedure to find the correct phase to apply.

The SHG signals are arranged to give the MIIPS trace. Each column is a SHG spectrum reading.
MIIPS iterates on this procedure to find the correct phase to apply.

At each frequency, the peak signal is taken to give $\delta_\omega(\omega)$.

From this, $\phi^m$ is generated as:

$$\phi^m = \gamma^2 A \sin[\gamma \omega - \delta_\omega(\omega)]$$

MIIPS iterates on this procedure to find the correct phase to apply.

Knowing that $\phi^m + \phi^m = 0$, we integrate $\phi^m$ to find:

$$\phi = -\gamma^2 A \int \sin[\gamma \omega - \delta_\omega(\omega)] d\omega$$

Now start the next iteration, by reapplying the sin modulation.

$$\varphi = A \sin(\gamma \omega - \delta)$$
MIIPS iterates on this procedure to find the correct phase to apply.

The SHG signals are arranged to give the MIIPS trace. Each column is a SHG spectrum reading.

MIIPS iterates on this procedure to find the correct phase to apply.

At each frequency, the peak signal is taken to give $\delta_\text{SHG}(\omega)$.

From this, $\varphi''$ is generated as:

$$\varphi'' = \gamma A \sin(\omega - \delta_\text{SHG}(\omega))$$

MIIPS iterates on this procedure to find the correct phase to apply.

Knowing that $\varphi'' + \varphi'' = 0$, we integrate $\varphi''$ to find

$$\phi = -\gamma A \int \sin(\omega - \delta_\text{SHG}(\omega)) d\omega$$

Red curve is correction from this iteration, blue curve is total correction from all iterations.
MIIPS iterates on this procedure to find the correct phase to apply.

Now start the next iteration, by reapplying the sin modulation.

\[ \varphi = A \sin(\gamma \omega - \delta) \]

The SHG signals are arranged to give the MIIPS trace. Each column is a SHG spectrum reading.
MIIPS iterates on this procedure to find the correct phase to apply.

MATLAB simulations demonstrate MIIPS ability to correct unknown phase profiles

- MIIPS trace, sin wave scanned over 4m
- Time reconstruction of pulse
  - Solid red = TL pulse
  - Dashed red = initial pulse
  - Blue = pulse after current iteration
- Phase profile of pulse
  - Red = initial phase profile of pulse
  - Blue = MIIPS determined phase profile after each iteration
A MIIPS based shaper was built in one of David Reis’s building 40 labs.

- Shaping done between oscillator and regen amplifier
  - Phase profile maintained through amplifier
- SLM is CRi, dual mask 128 pixels
- Lens is 6” achromat
- Grating is 300 l/mm

A LabVIEW VI was programmed to talk with instruments and do MIIPS
The setup was used to compress the oscillator pulse.

- SHG spectrum from OIO USB2000
- Temporal profile measured with A.P.E. SPIDER
  - Dotted red = TL pulse
  - Blue = temporal profile after each iteration
    (Iteration 0 is pulse with 0 phase applied on SLM)
- Spectrum measured with SPIDER
  - Slight positive quadratic phase from path difference between MIIPS SHG and SPIDER.
  - Higher order negative phase at wings likely due to low SPIDER signal

There is still room for improvement and work to do.

- Switch from lens-based 4f shaper to all reflective
- Improve calibration routines for determining applied phase
- Increase routine speed
- More options in VI
- Route the shaped pulse through the Regen amplifier

There are plans to use the pulse shaper for HHG experiments.

- SLM allows phase and amplitude shaping
- Plan to explore pulse bandwidth and phase profile parameter space to see effect on HHG signals.
- Next gen FELs may be HHG-seeded
  - We hope to gain control over spectral properties of HHG
    - Linewidth of each harmonic, etc.
Bibliography


