Pulse Shaping with MIIPS

SASS 8/22/2012

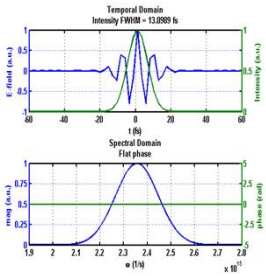
David Nicholson

Outline

- Pulse shaping introduction
- MIIPS
  - MATLAB Simulations
  - Actual implementation

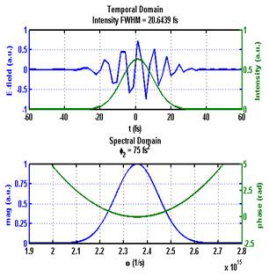
Laser pulses can be defined in the time or frequency domains

- Electric field of pulse is equivalently defined in both
  - Time: $\tilde{\mathbf{E}}(t) = \mathcal{F}\left[\tilde{\mathbf{E}}(\omega)\right]$
  - Freq.: $\tilde{\mathbf{E}}(\omega) = \mathcal{F}\left[\tilde{\mathbf{E}}(t)\right]$
- Typical fourier transform properties apply

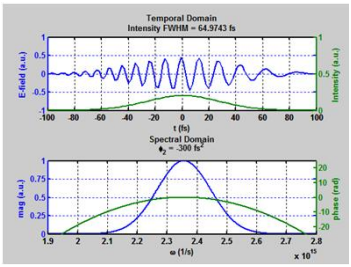


The spectral phase components determine the temporal structure of pulse

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

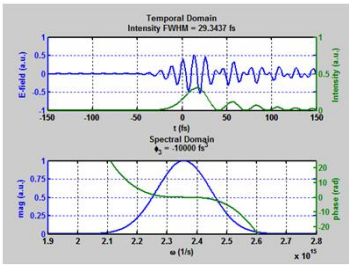


2nd Order Phase



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

3rd Order Phase



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

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

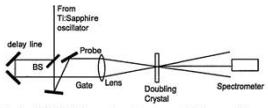
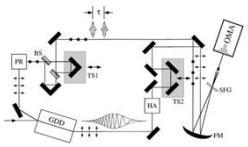
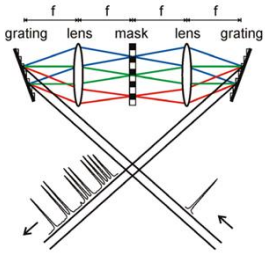


Fig. 1. SHG FROG experimental setup. BS, Beam splitter.



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



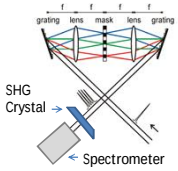
- Once you have measured the phase, a simple way to correct it, or apply any phase is the 4-f shaper
- Spectral components modulated in fourier plane by SLM

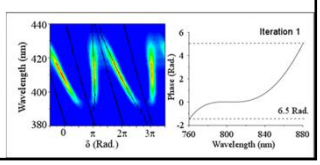
MIIPS allows for pulse characterization and shaping in a single 4-f device.

- Takes advantage of SHG sensitivity to phase profile of input pulse

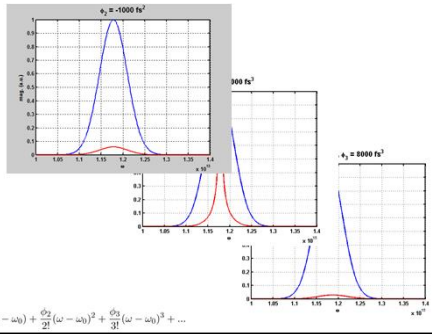
$$S^{(2)}(2\omega) \propto \left| \int \left|\tilde{E}(\omega+\Omega)\right| \left|\tilde{E}(\omega-\Omega)\right| \exp\left\{ i\left[\phi(\omega+\Omega) + \phi(\omega-\Omega)\right]\right\} d\Omega \right|^2$$

- 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.



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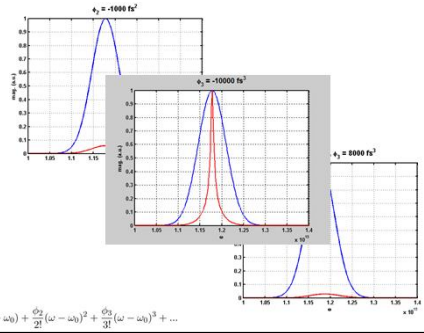

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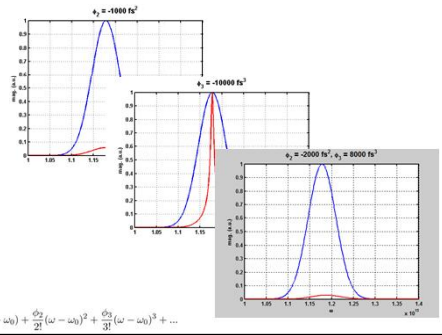

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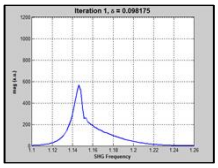
MIIPS leverages NL signals to measure the input pulse's phase profile.

- Input phase is unknown ϕ
- 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 $\phi = -\gamma^2 A \iint \sin[\gamma\omega - \delta_m(\omega)] d^2\omega$

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



Apply reference phase on top of unknown phase, scan the δ parameter.

$$\varphi = A\sin(\gamma\omega - \delta)$$

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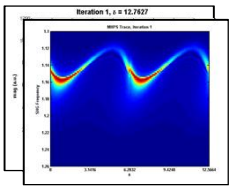
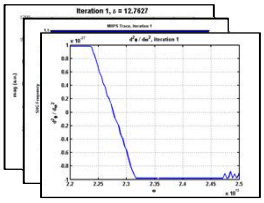


The SHG signals are arranged to give the MIIPS trace. Each column is a SHG spectrum reading.

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



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

From this, φ'' is generated as: $\varphi'' = \gamma^2 A \sin[\gamma\omega - \delta_m(\omega)]$

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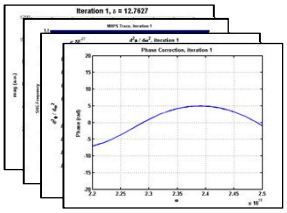

Knowing that $\phi'' + \varphi'' = 0$, we integrate φ'' to find:

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

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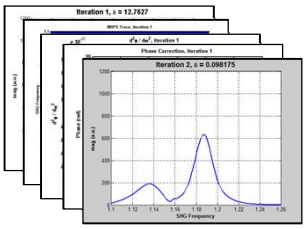

Now start the next iteration, by reapplying the sin modulation.

$$\varphi = A \sin(\gamma\omega - \delta)$$

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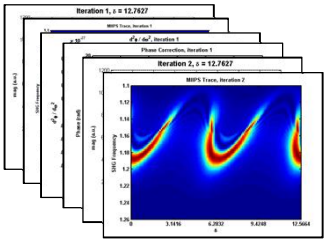

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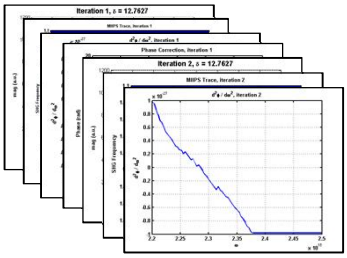

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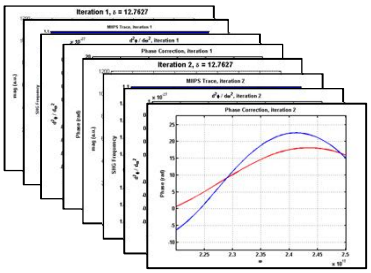

Red curve is correction from this iteration, blue curve is total correction from all iterations

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

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

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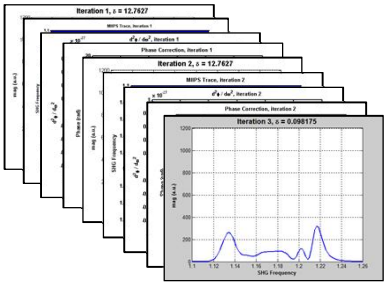

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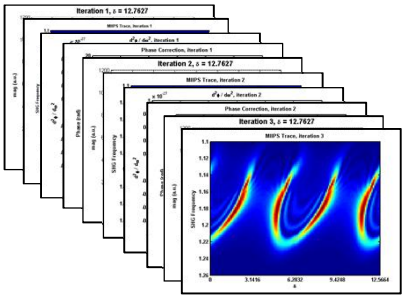

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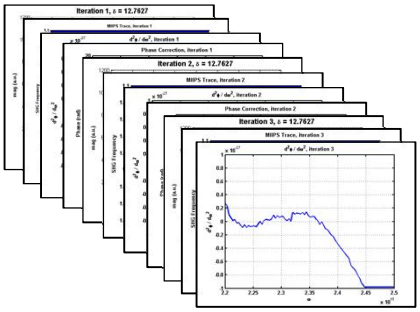

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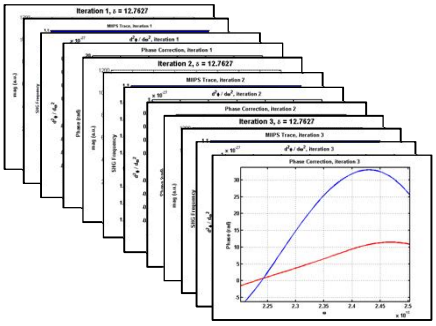

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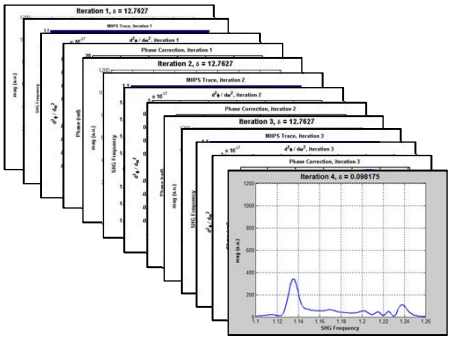
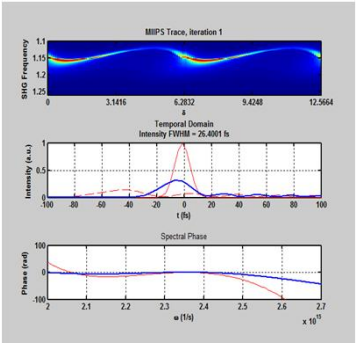
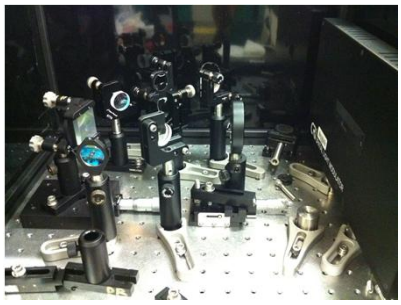


MATLAB simulations demonstrate MIIPS ability to correct unknown phase profiles



- MIIPS trace, sin wave scanned over 4π
- 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

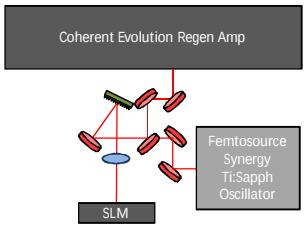
A MIIPS based shaper was built in one of David Reis's building 40 labs.



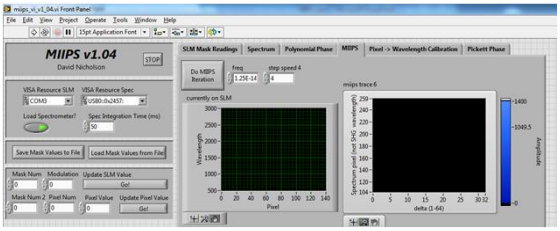
Actual setup

A MIIPS based shaper was built in one of David Reis's building 40 lab.

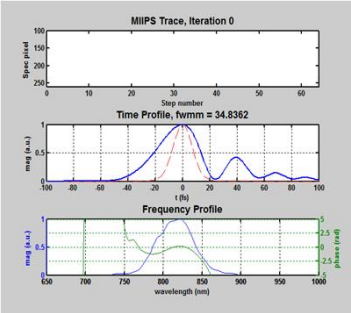
- Shaping done between oscillator and regen amplifier
  - Phase profile maintained through amplifier
- SLM is CRi, dual mask 128 pixels
- Lens is 6" achromat
- Grating is 300 l/mm



A LabVIEW VI was programmed to talk with instruments and do MIIPS



The setup was used to compress the oscillator pulse.



- SHG spectrum from OO 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

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