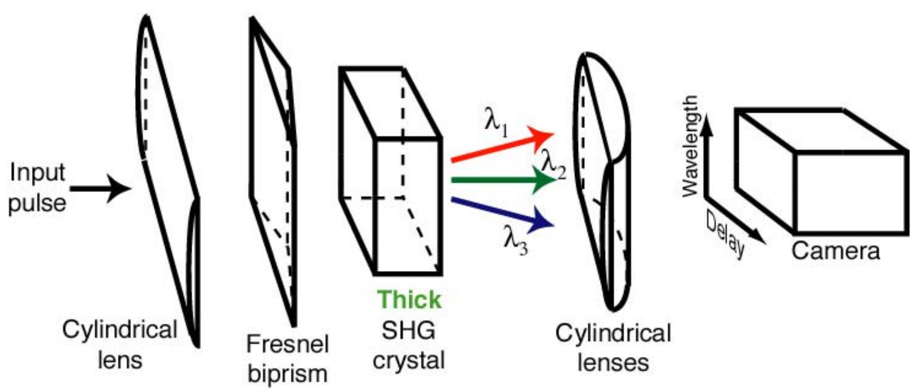
Numerical Simulations of an Ultrasimple Ultrashort-Laser-Pulse Measurement Device—GRENOUILLE

Xuan Liu and R. Trebino
School of Physics, Georgia Institute of Technology, GA 30332 USA
Arlee V. Smith
Sandia National Laboratories, Albuquerque, NM 87185, USA



Supported by NSF and Georgia Institute of Technology

Outline

Measure ultrashort pulses using the FROG technique

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Simplification of FROG set up: the GRENOUILLE device

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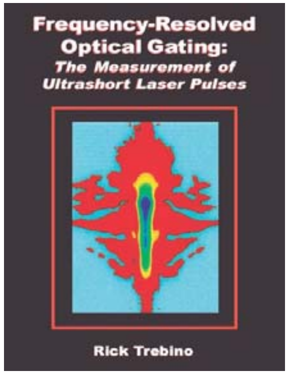
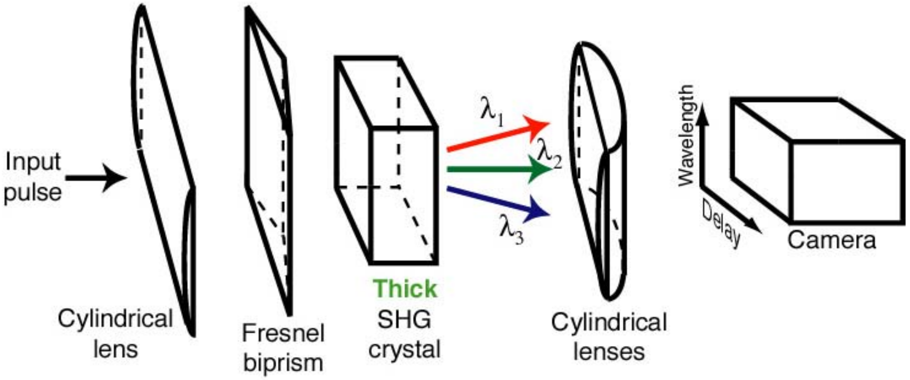
Numerical Simulations of GRENOUILLE

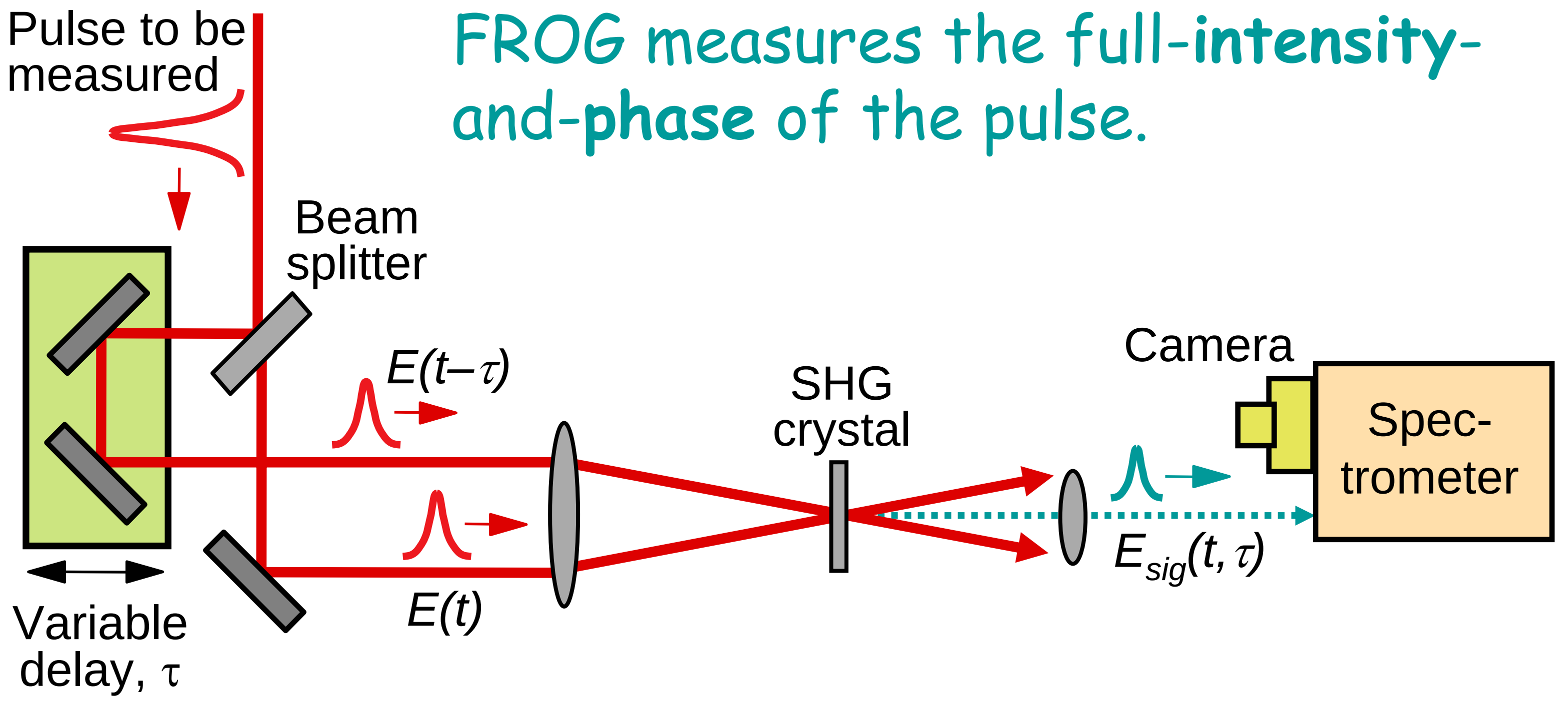




Frequency Resolved Optical Gating (FROG)

FROG involves gating the pulse with a variably delayed replica of itself in an instantaneous nonlinear-optical medium and then spectrally resolving the gated pulse vs. delay.

FROG measures the full-**intensity**-and-**phase** of the pulse.



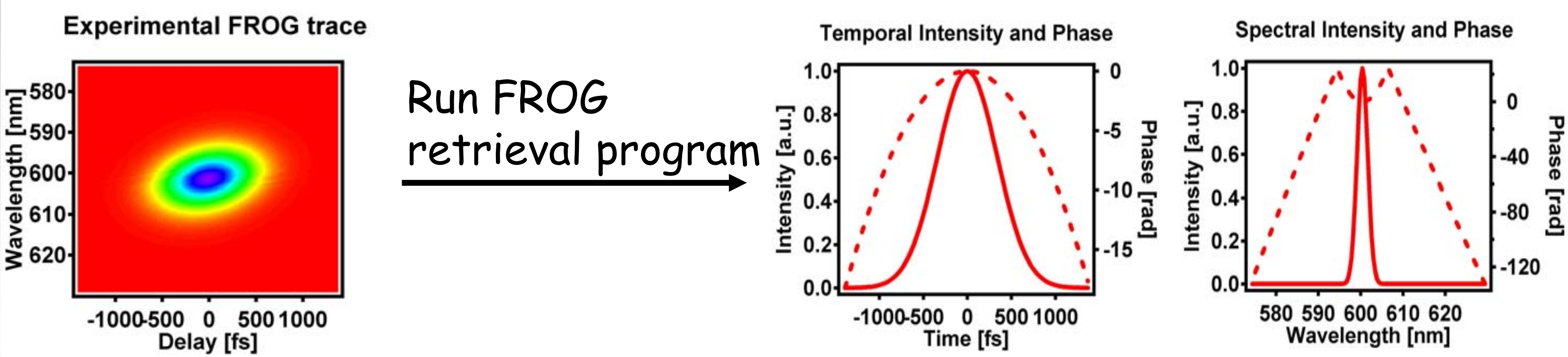
The FROG Technique

The FROG trace is a spectrogram of E(t). The mathematical expression for the FROG trace:

$$I_{FROG}(\omega,\tau) \propto \left| \int E(t)\, g(t-\tau) \exp(-i\omega t)\, dt \right|^2$$

Where $g(t-\tau) = E(t-\tau)$ is the gate function.

We must invert this integral equation and solve for the unknown pulse.This integral-inversion problem is the 2D phase-retrieval problem, for which the solution exists and is (essentially) unique. And simple algorithms exist for finding it.



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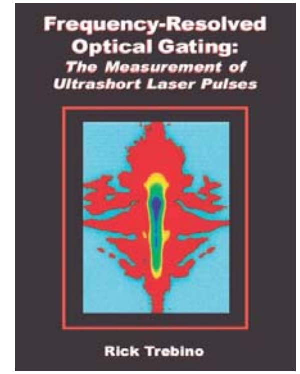
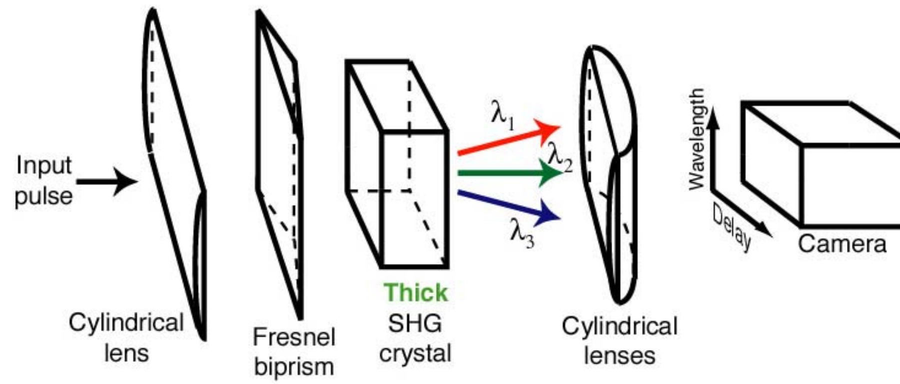
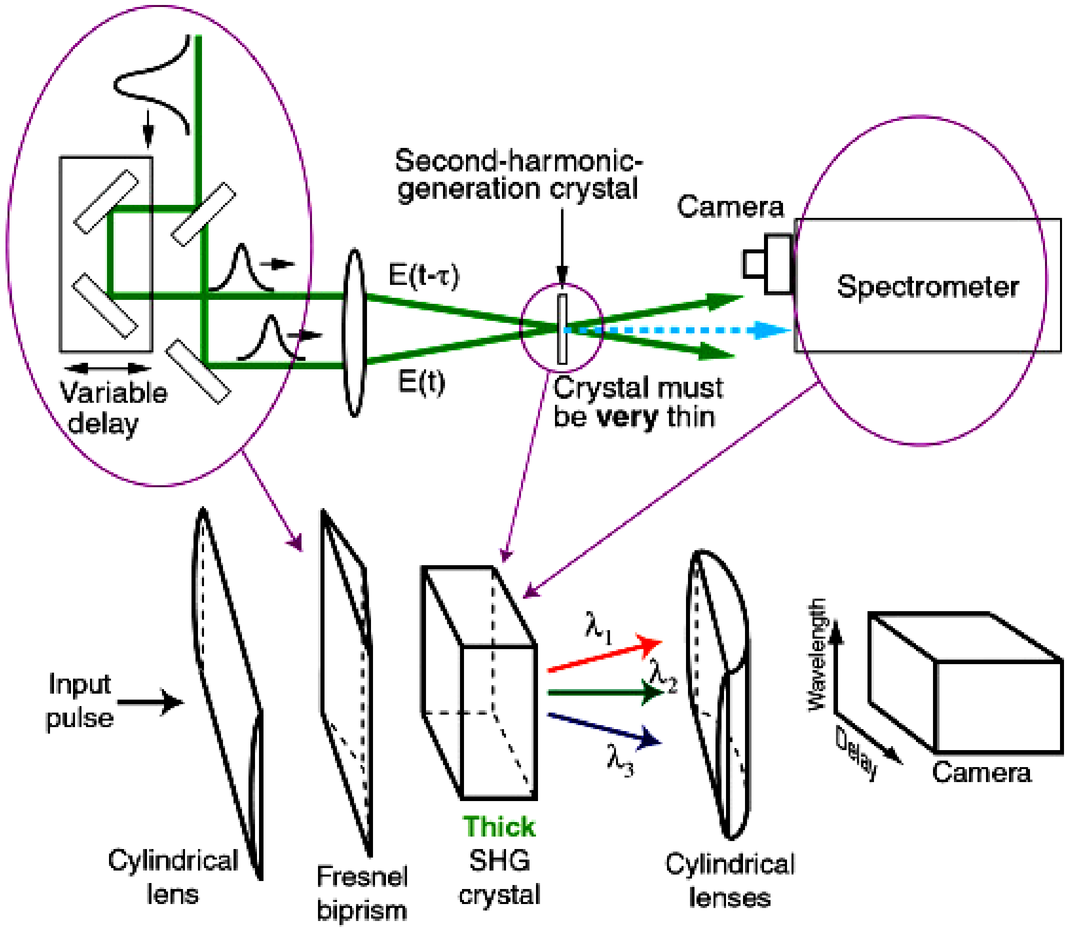




GRating-Eliminated No-nonsense Observation of Ultrafast Incident Laser Light E-fields (GRENOUILLE)

FROG:
Frequency-
Resolved
Optical
Gating

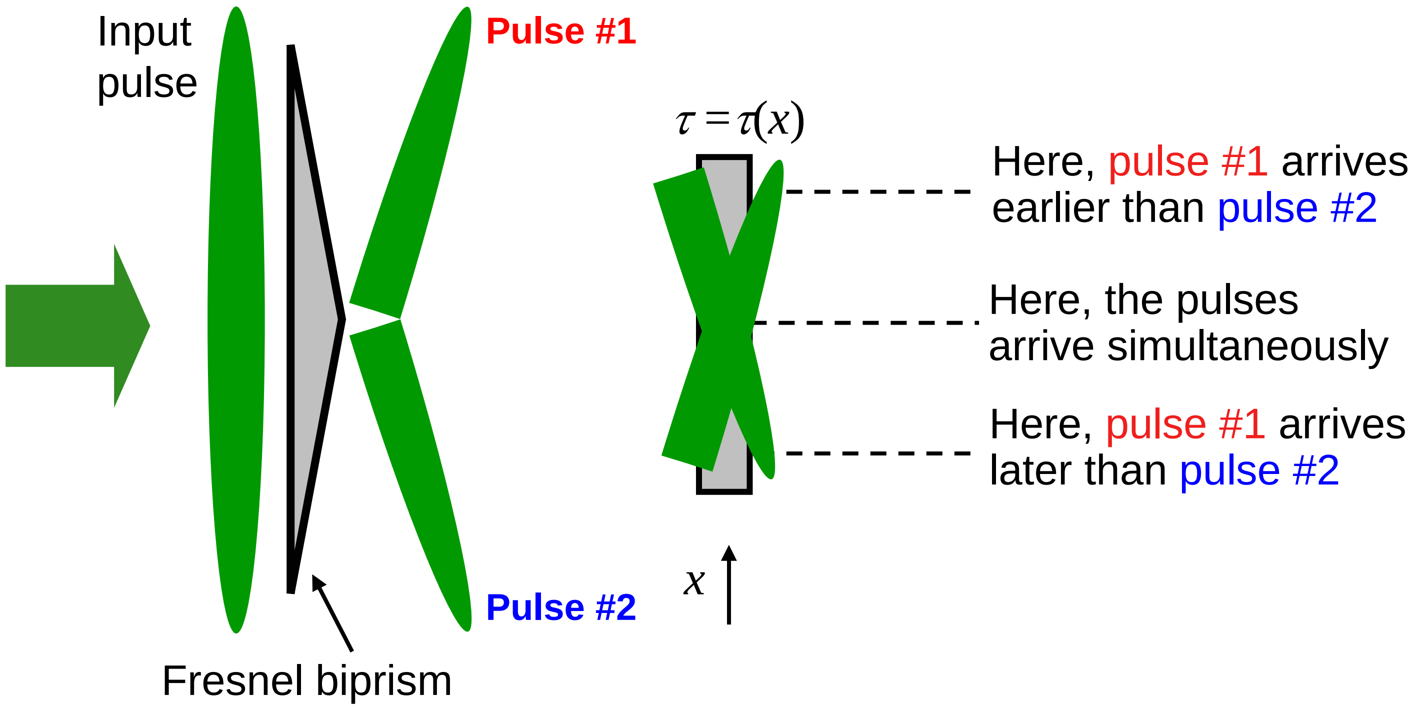
GRENOUILLE:
GRating-
Eliminated
No-nonsense
Observation of
Ultrafast
Incident
Laser
Light
E-fields



A *single* optic (a Fresnel biprism) replaces the *entire* delay line, and a *thick* SHG crystal replaces *both* the thin crystal *and* spectrometer.

The Fresnel Biprism

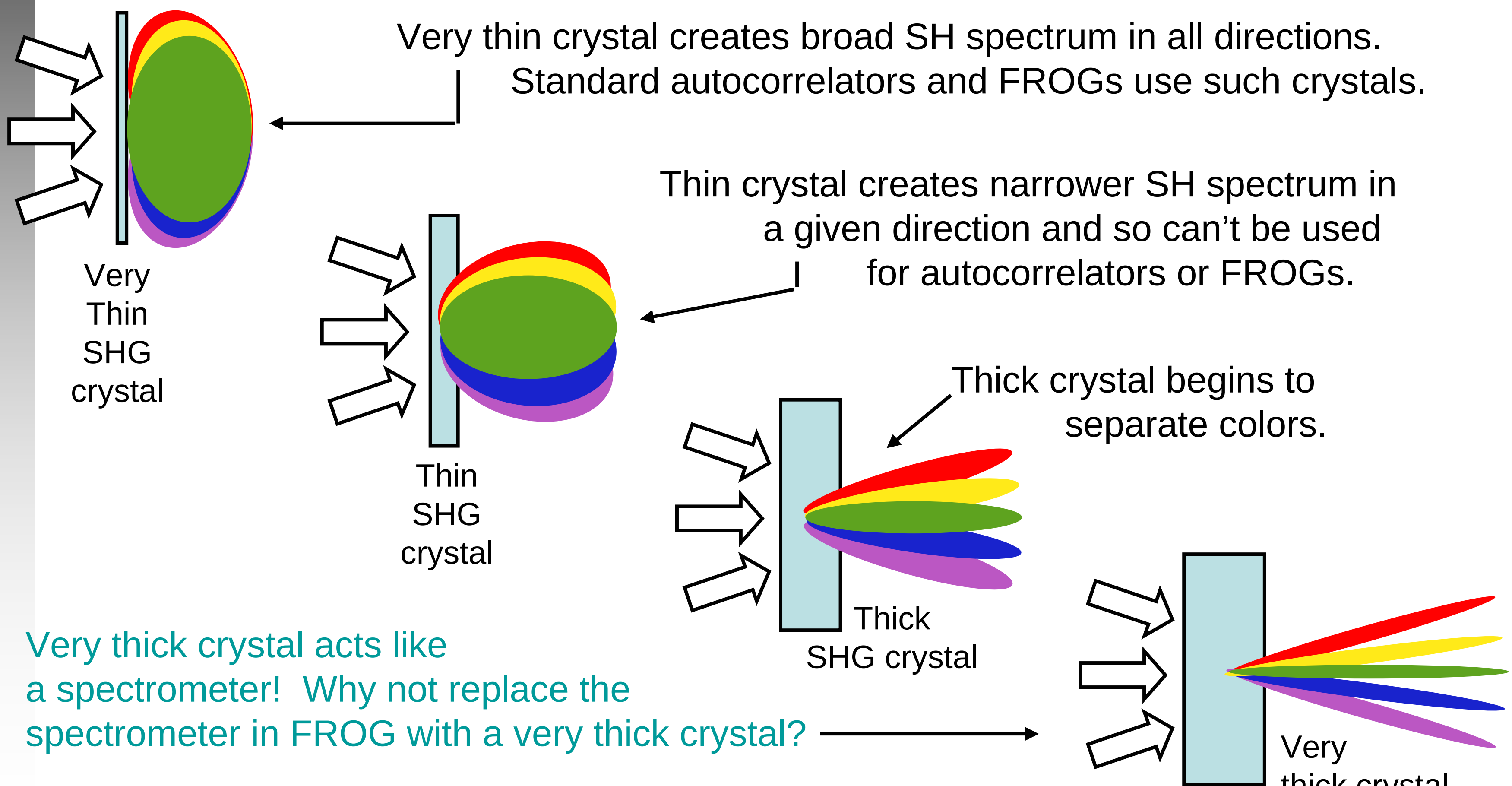
Crossing beams at a large angle maps delay onto transverse position.



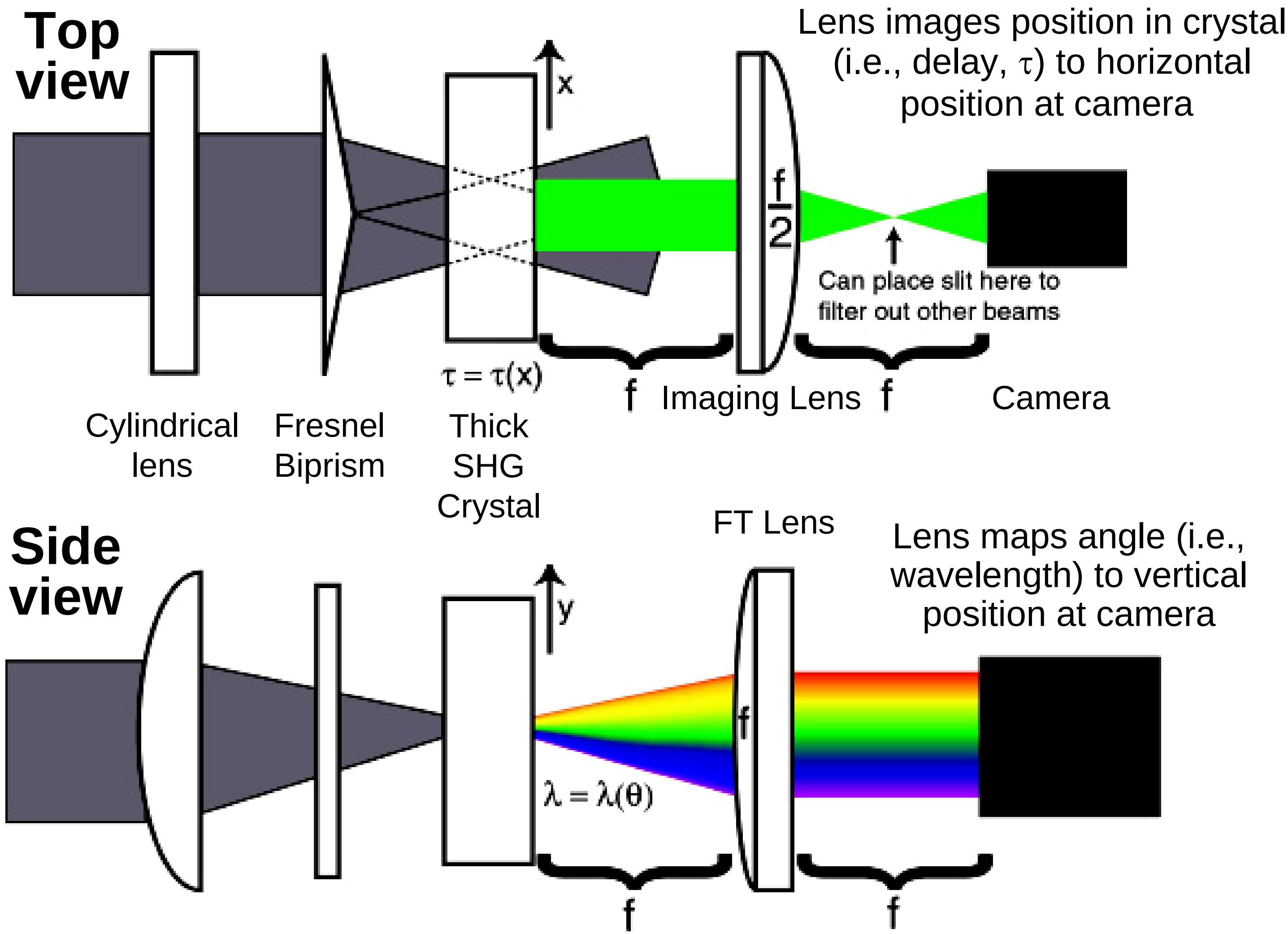
Even better, this design is amazingly compact and easy to use, and it never misaligns!

Crystal Thickness

Suppose white light with a large divergence angle impinges on an SHG crystal. The SH generated depends on the angle. And the angular width of the SH beam created varies inversely with the crystal thickness.



GRENOUILLE Beam Geometry

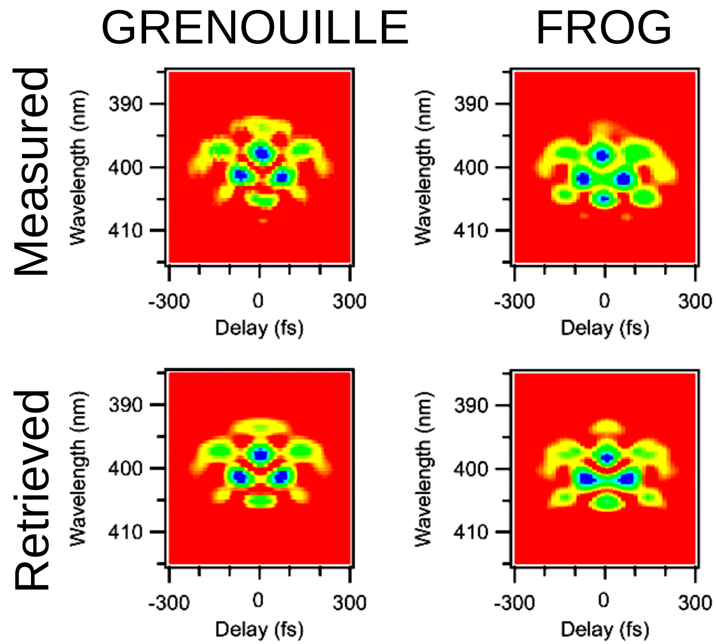


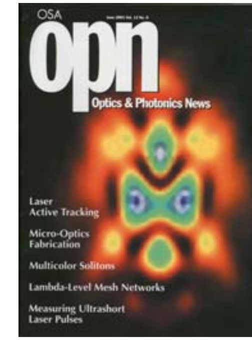
Yields a complete single-shot FROG. Uses the standard FROG algorithm. Never misaligns. Is more sensitive. Measures spatio-temporal distortions*

*Akturk, S., et al., Measuring pulse-front tilt in ultrashort pulses using GRENOUILLE. Opt. Expr., 2003. 11(5): p. 491-501.
Akturk, S., et al., Measuring spatial chirp in ultrashort pulses using single-shot Frequency-Resolved Optical Gating. Opt. Expr., 2003. 11(1): p. 68-78

Testing GRENOUILLE

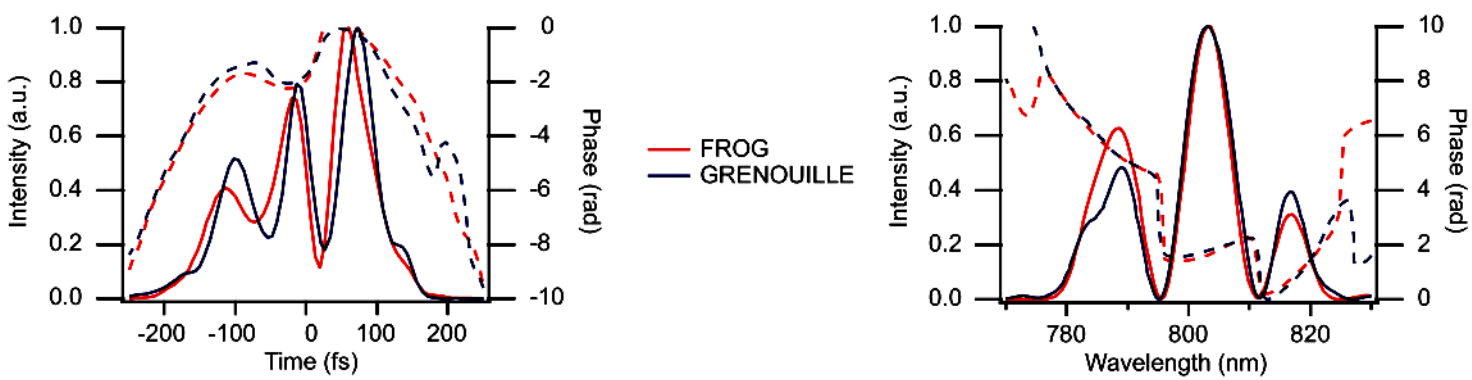
Compare a GRENOUILLE measurement of a pulse with a tried-and-true FROG measurement of the same pulse:





Read more about GRENOUILLE in the cover story of OPN, June 2001

Retrieved pulse in the time and frequency domains



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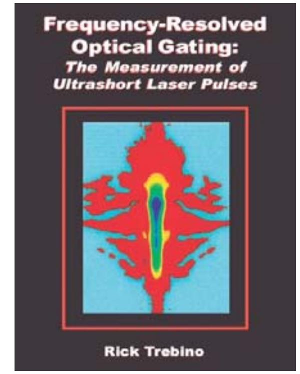
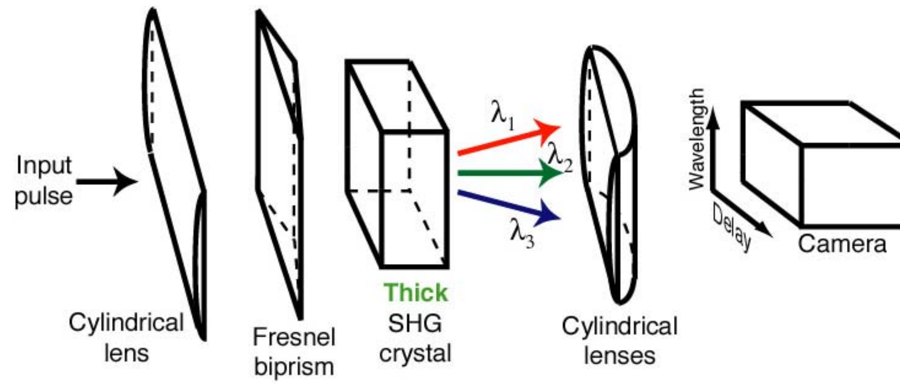
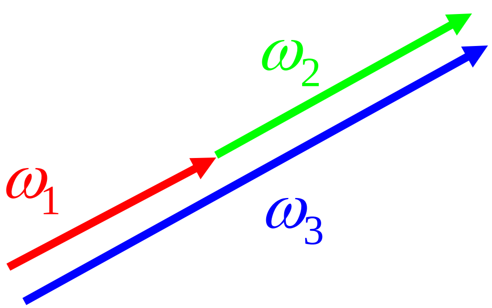
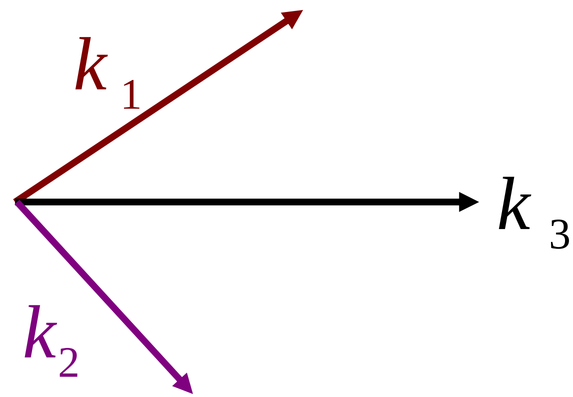




Nonlinear Process in GRENOUILLE

GRENOUILLE uses the second-order nonlinearities of a thick crystal with relatively tightly focused and broadband pulses. We must allow not only SHG processes, but also all possible sum-frequency-generation processes, both collinear and non-collinear.





All the plane wave pairs have to satisfy:

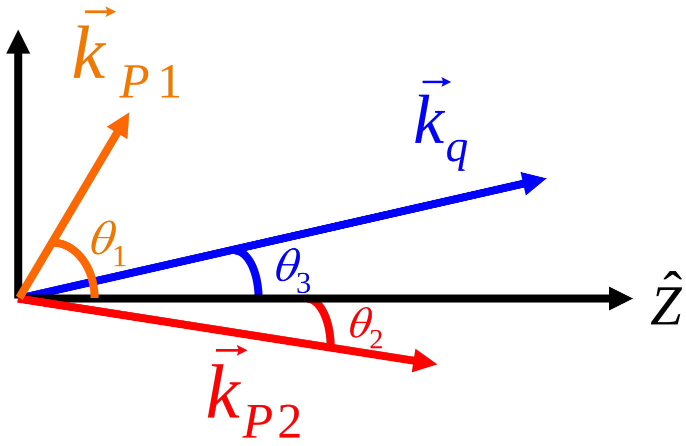
$$\omega_1 + \omega_2 = \omega_3 \qquad k_{1y} + k_{2y} = k_{3y}$$

Sum Frequency Generation

No pump depletion:

$$\frac{\partial E_3(k_{3y},\omega_3,z)}{\partial z} = \iint i\,\frac{d_{eff}\,\omega_3}{c\tilde{n}_3}\exp(-i\Delta k_z z)\times$$

$$E_1(k_{1y},\omega_1,z)E_2(k_{3y}-k_{1y},\omega_3-\omega_1,z)\,dk_{1y}\,d\omega_1$$



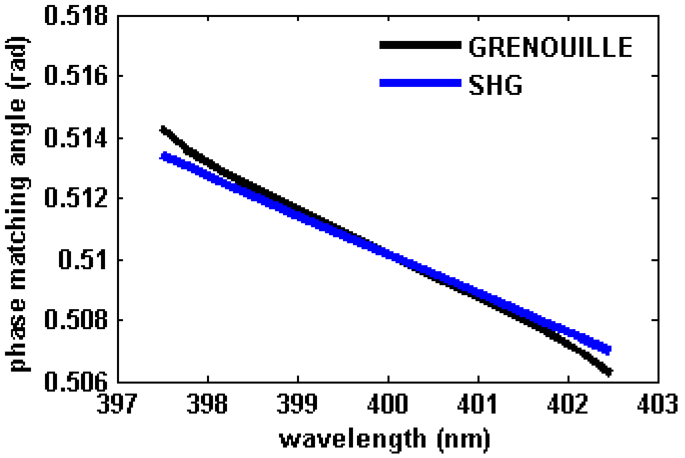
Phase mismatch:

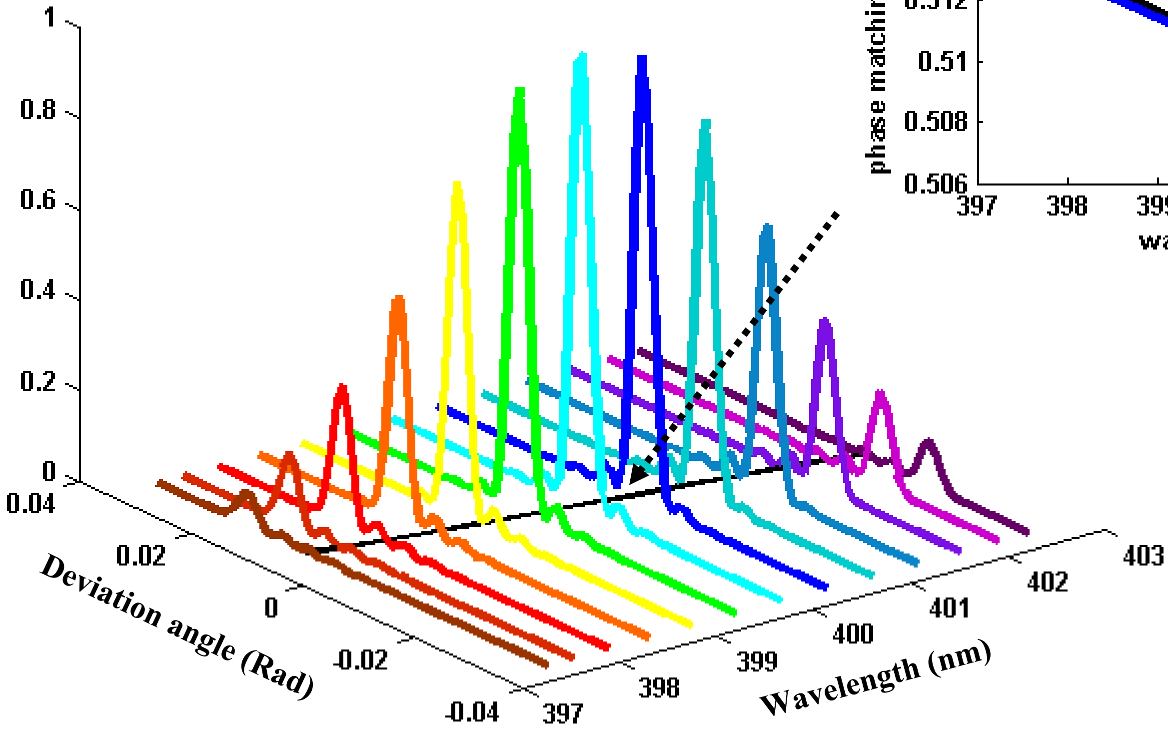
$$\Delta k_{qz} = \frac{\omega_3 n_e(\omega_3,\theta_3)}{c}\cos\theta_3 -$$

$$\frac{\omega_1 n_o(\omega_1)}{c}\cos\theta_1 - \frac{\omega_2 n_o(\omega_2)}{c}\cos\theta_2$$

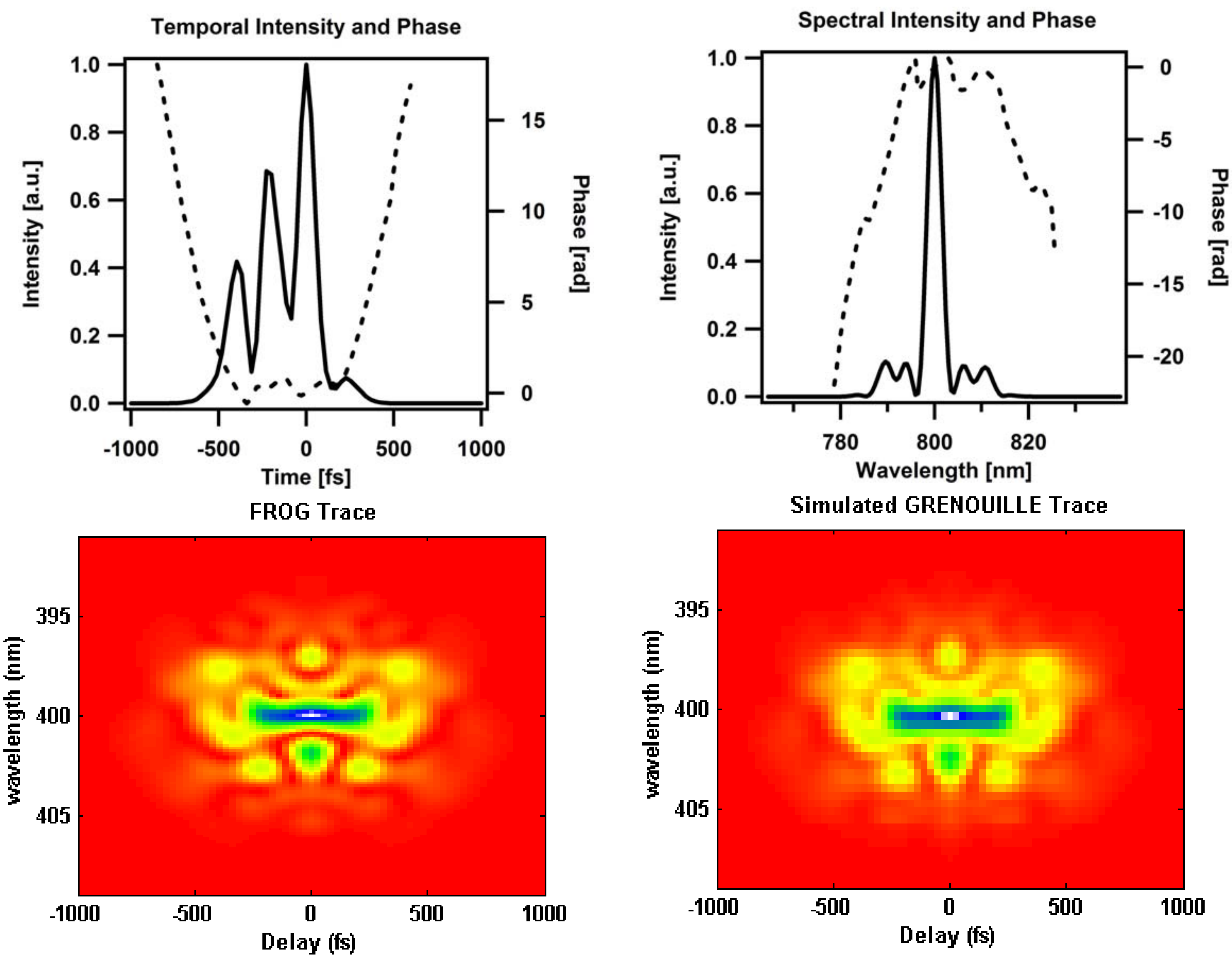
Zero Delay Spectrum at Different Angles

The deviation angle vs. spectrum plot confirmed that the crystal does work like a spectrometer.

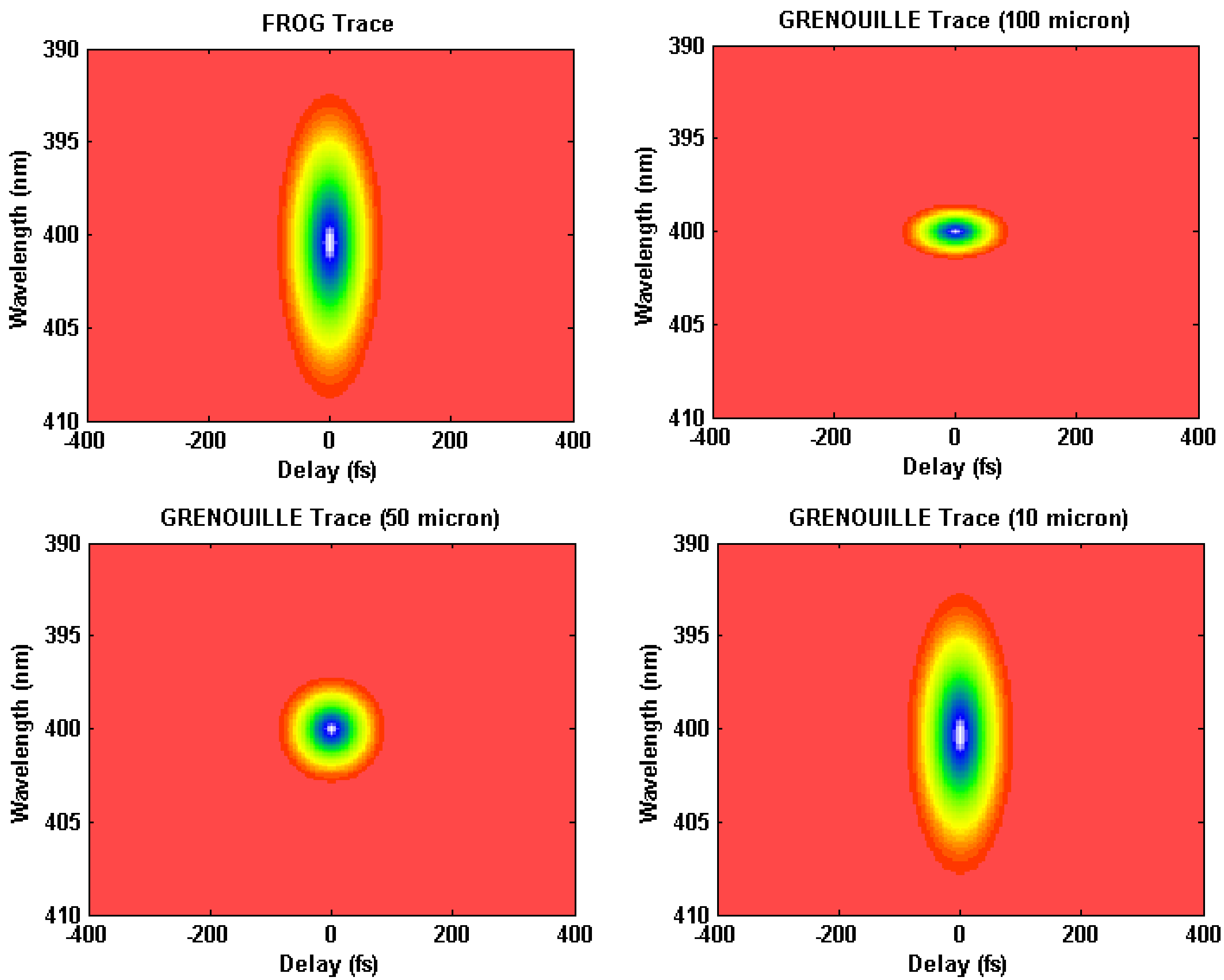




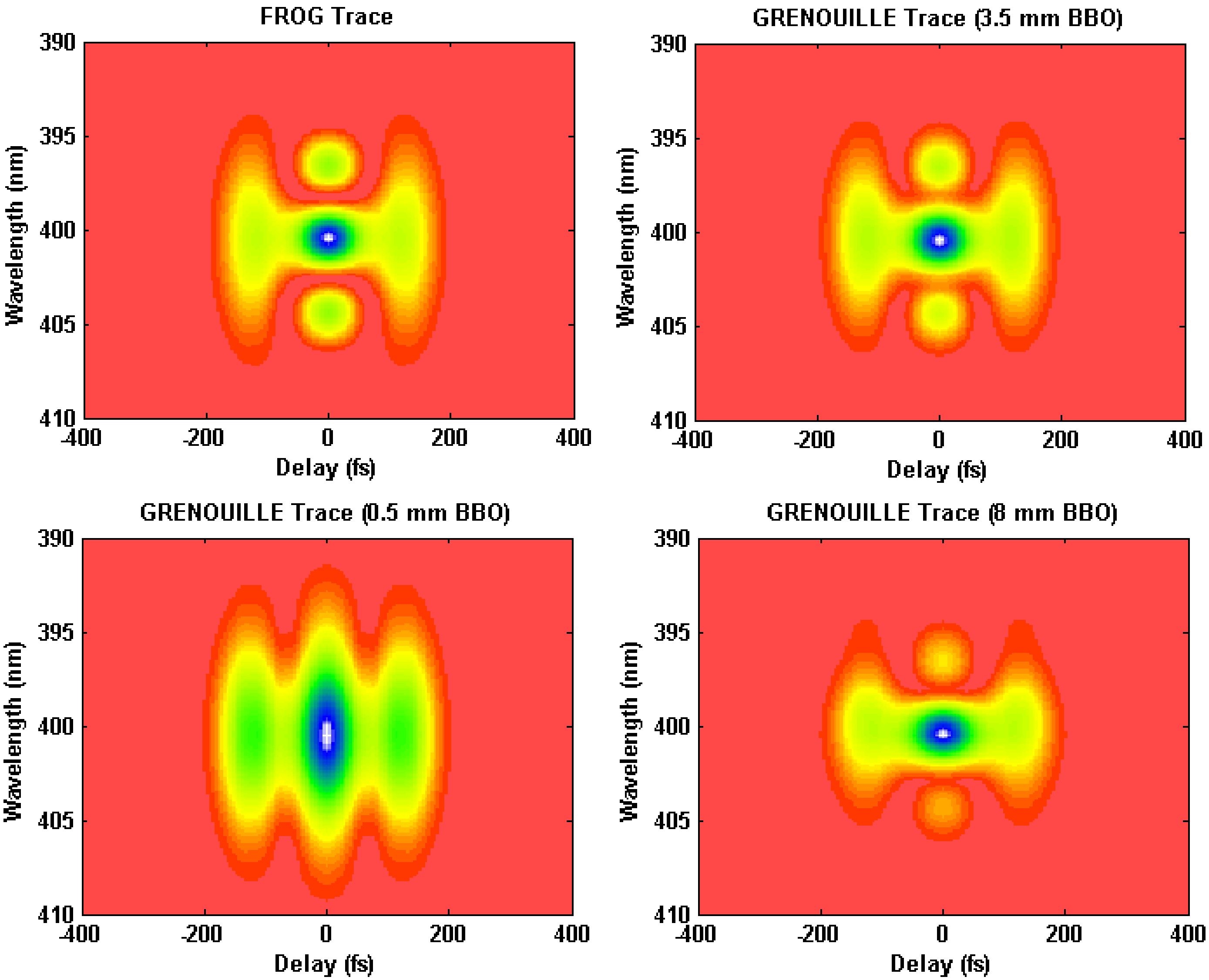
Simulated GRENOUILLE Trace



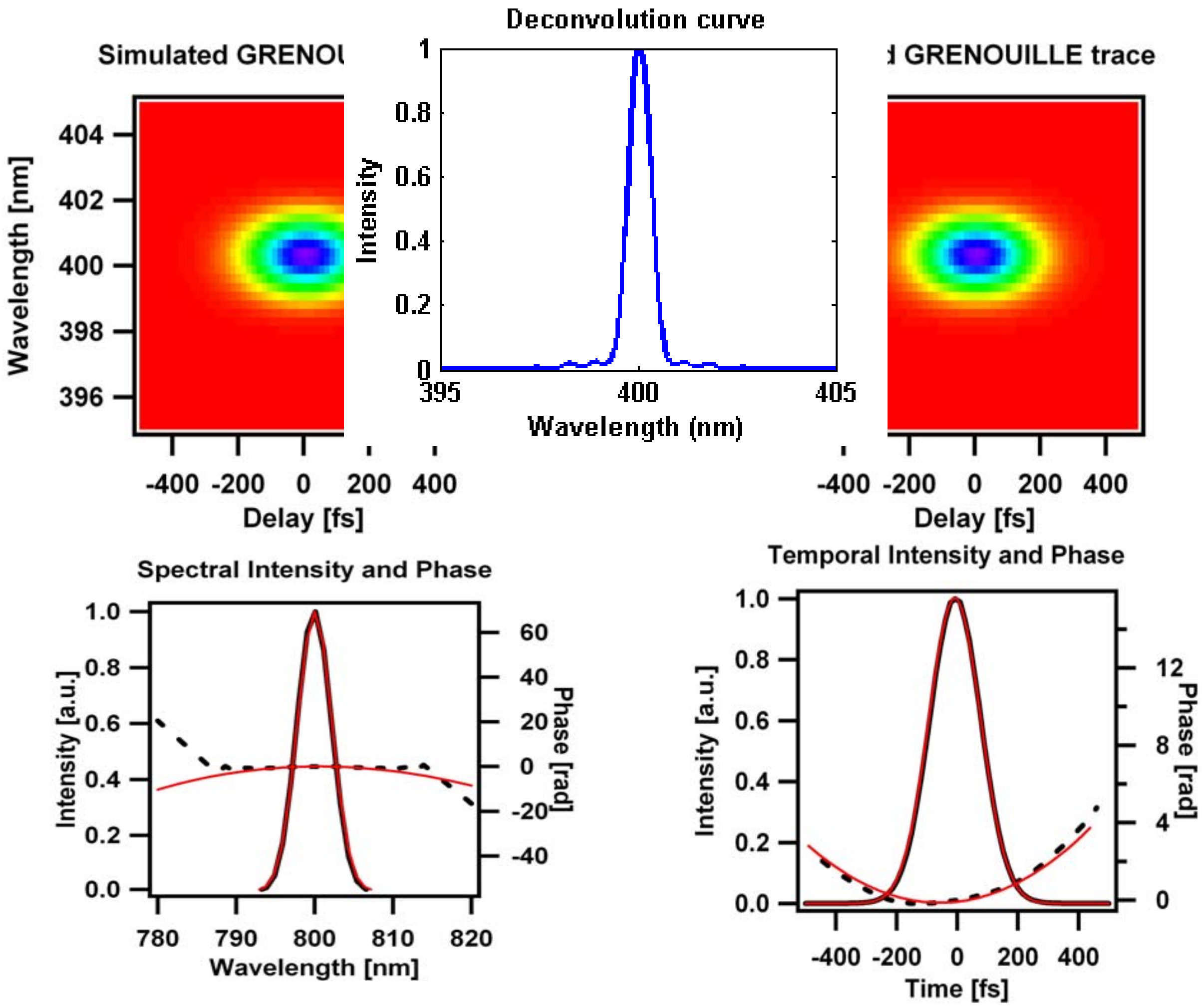
Tight Focus


FROG Trace
GRENOUILLE Trace (100 micron)
GRENOUILLE Trace (50 micron)
GRENOUILLE Trace (10 micron)
Wavelength (nm)
Delay (fs)
390
395
400
405
410
-400
-200
0
200
400

Crystal Thickness



Simulated GRENOUILLE Trace and Its Retrieval



200 fs chirped pulse, The FROG (rms) error was 0.001148.

Conclusion

- We numerically simulated the performance of GRENOUILLE, which involves the sum frequency generation of tightly focused broadband input beams.

- Using the full Sellmeier equation, we can take into account all of the dispersion effects.

- In order to improve GRENOUILLE's spectral resolution when high accuracy is required, we numerically deconvolve the spectral response of the device with a efficiency curve that we derive from our simulations. We show that accurate measurements are easily obtained for properly designed device.