united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
**abdus salam**
international centre for theoretical physics

SMR 1302 - 10

**WINTER SCHOOL ON LASER SPECTROSCOPY AND APPLICATIONS**

**19 February - 2 March 2001**

# *Characterization of visible, UV and NIR femtosecond pulses*

## *Lecture II*

E. RIEDLE
Ludwig-Maximilians-Universitaet Munich
Lehrstuhl fuer Biomolekular Optik - Sektion Physik
Munich, Germany

***These are preliminary lecture notes, intended only for distribution to participants.***

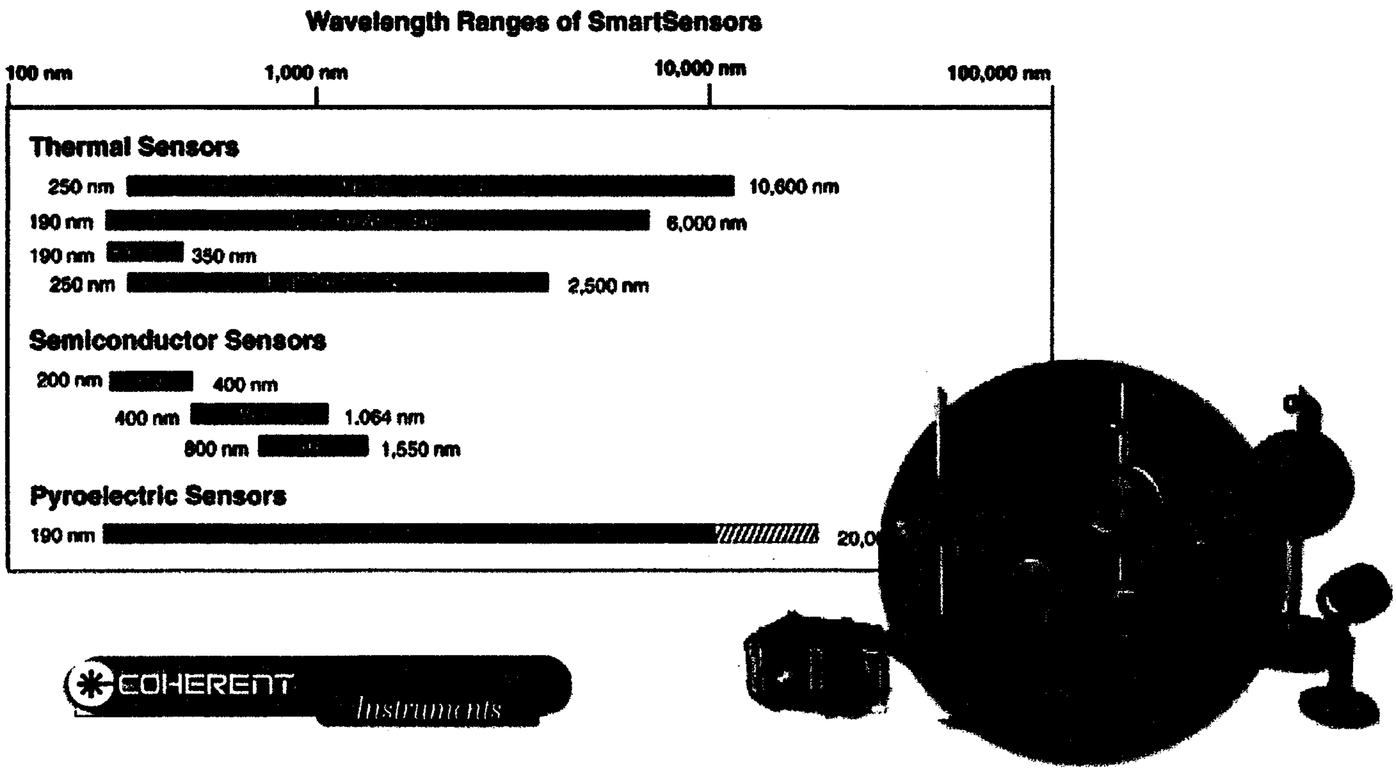
# Characterization of visible, UV and NIR femtosecond pulses

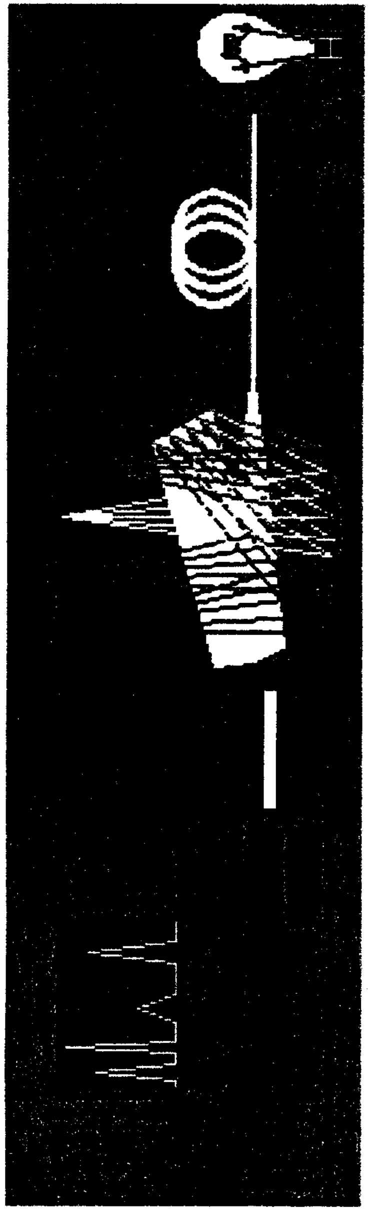
- pulse energy
- spectral distribution
- beam profile
- intensity autocorrelation
- fringe resolved autocorrelation
- crosscorrelation
- FROG: frequency resolved optical gating
- SPIDER: spectral phase interferometry for direct electric-field reconstruction
- concluding remarks

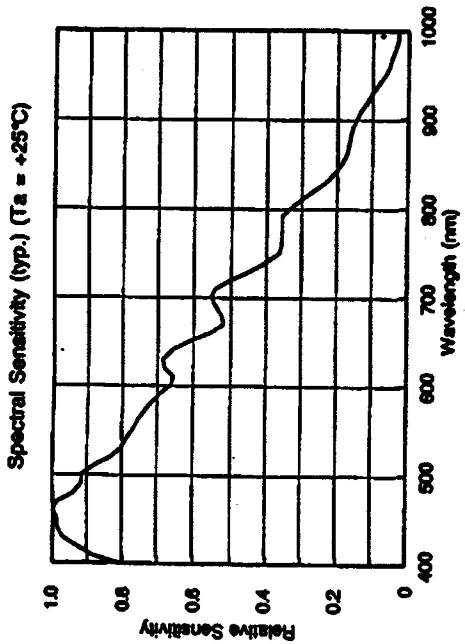
WINTER SCHOOL ON LASER SPECTROSCOPY AND APPLICATIONS (19 February - 2 March 2001) E. Riedle

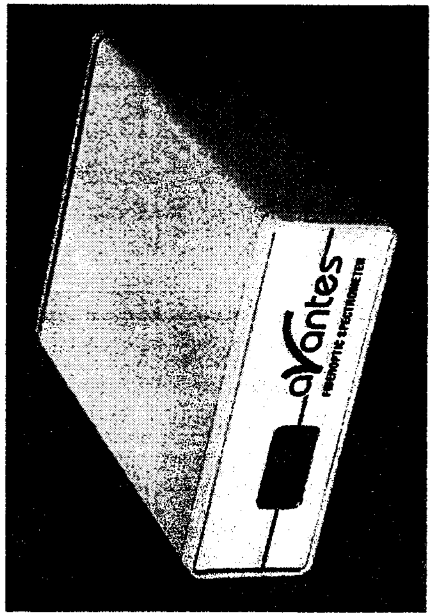
---

## Powermeter for Femtosecond Pulses ???



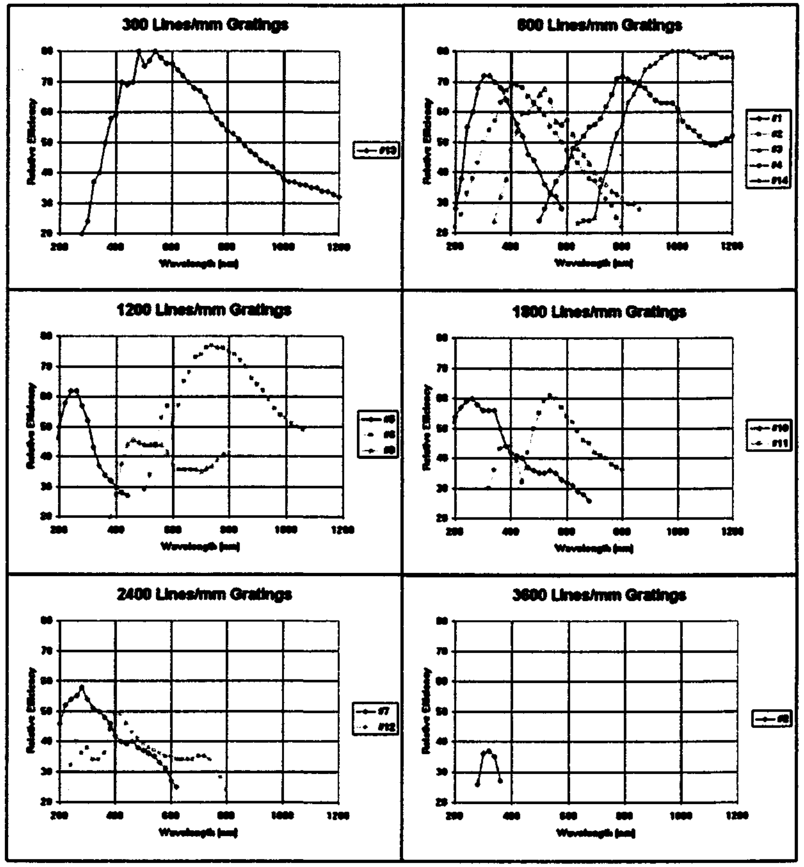


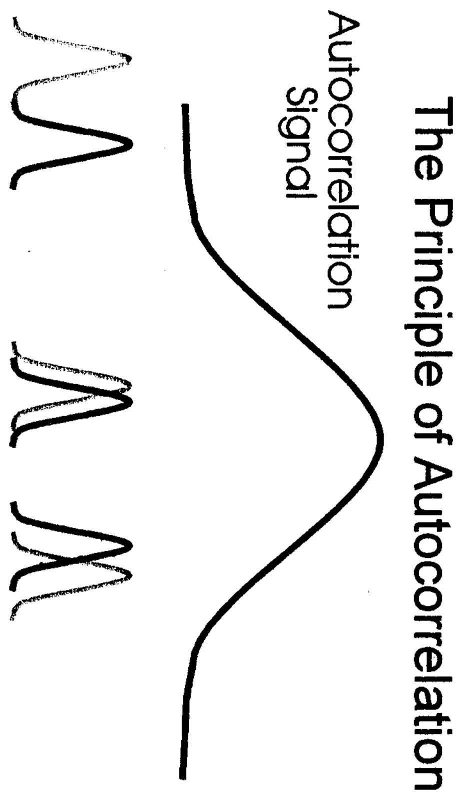


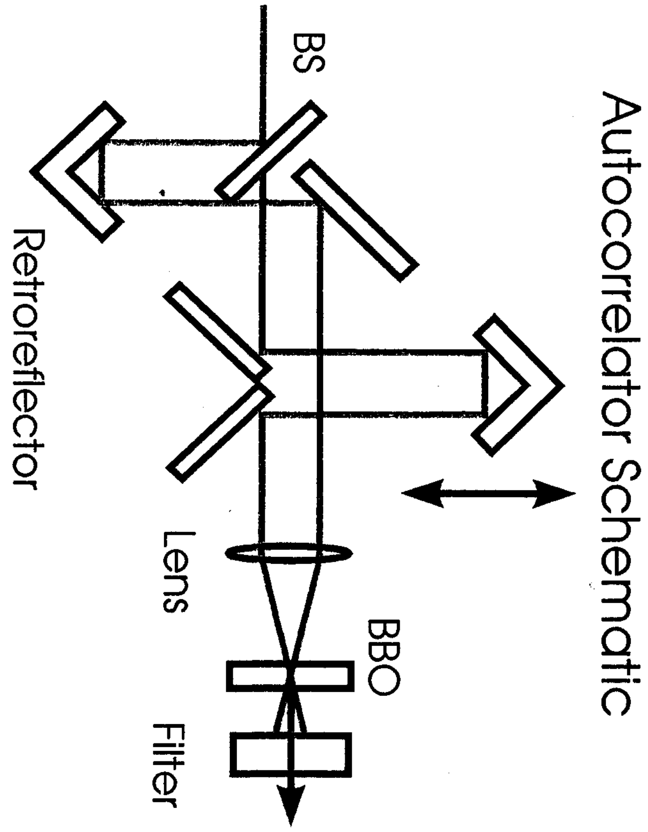




avantes

# Grating Efficiency Curves






## Autocorrelation Measurements

Correlation function: $A_{cor}(\tau) = \int_{-\infty}^{\infty} I_{reference}(t) \cdot I_{sample}(t - \tau)\,dt$

The shape of a sample pulse is measured by observing the overlap with a shorter reference pulse at variable delay. A nonlinear detector records the signal.

Such a reference pulse is often not available and the sample pulse itself is used.

Intensity AC: $A_{AC}(\tau) = \int_{-\infty}^{\infty} I_{sample}(t) \cdot I_{sample}(t - \tau)\,dt$

Pulse: $E(t) = \mathcal{E}(t) \cdot e^{i\varphi(t)} \cdot e^{i\omega_l t}$

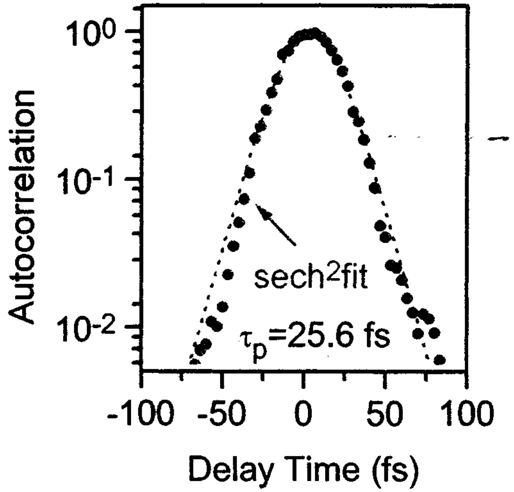
$\mathcal{E}(t)$ slowly varying envelope of the electric field

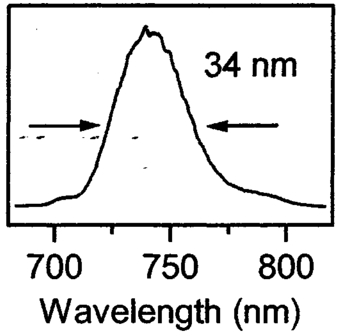
$\varphi(t)$ slowly varying phase

$\omega_l$ carrier frequency of laser

By suitable experimental observation all fast variations of the field and all spatial dependencies are averaged. Only the terms pertaining to $\mathcal{E}(t)$ are recorded.

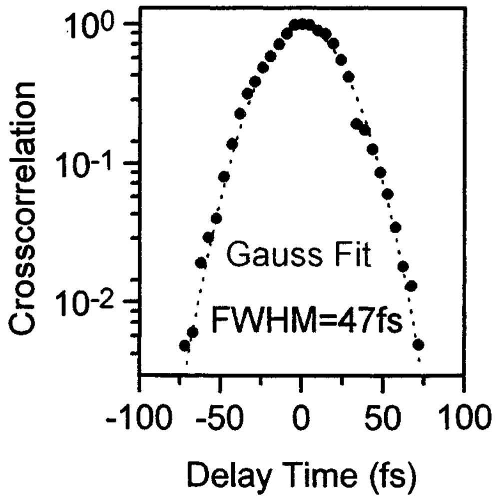
# Fundamental

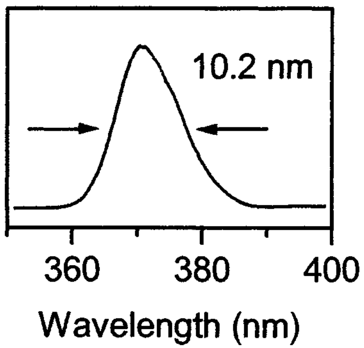



$\Delta\nu\Delta t = 0.47$

# 25 fs Second Harmonic Generation

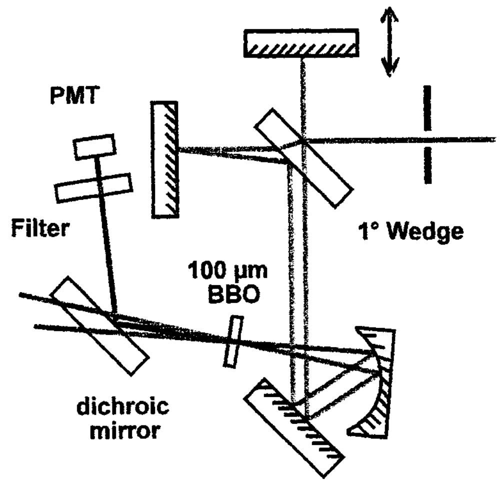


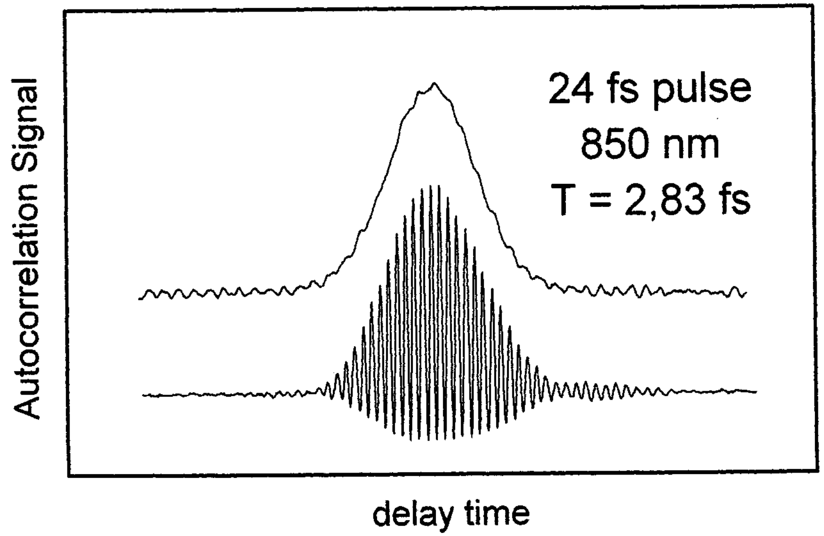




$\tau_{blue} \approx$ 25 fs

$\Delta\nu\Delta t = 0.55$

# Autocorrelation measurement of ultrashort pulses



In a Michelson interferometer (with second harmonic detection) there is no complete averaging and the phase of the electric field has be taken into account:

$$A_{AC;interferometric}(\tau) = \int_{-\infty}^{\infty} \left\{ \left[ E_1(t-\tau) + E_2(t) \right]^2 \right\}^2 dt$$

$$A_{AC}(\tau) = A(\tau) + \mathrm{Re}\left\{ 4\tilde{B}(\tau) e^{i\omega_1 \tau} \right\} + \mathrm{Re}\left\{ 2\tilde{C}(\tau) e^{2i\omega_1 \tau} \right\}$$

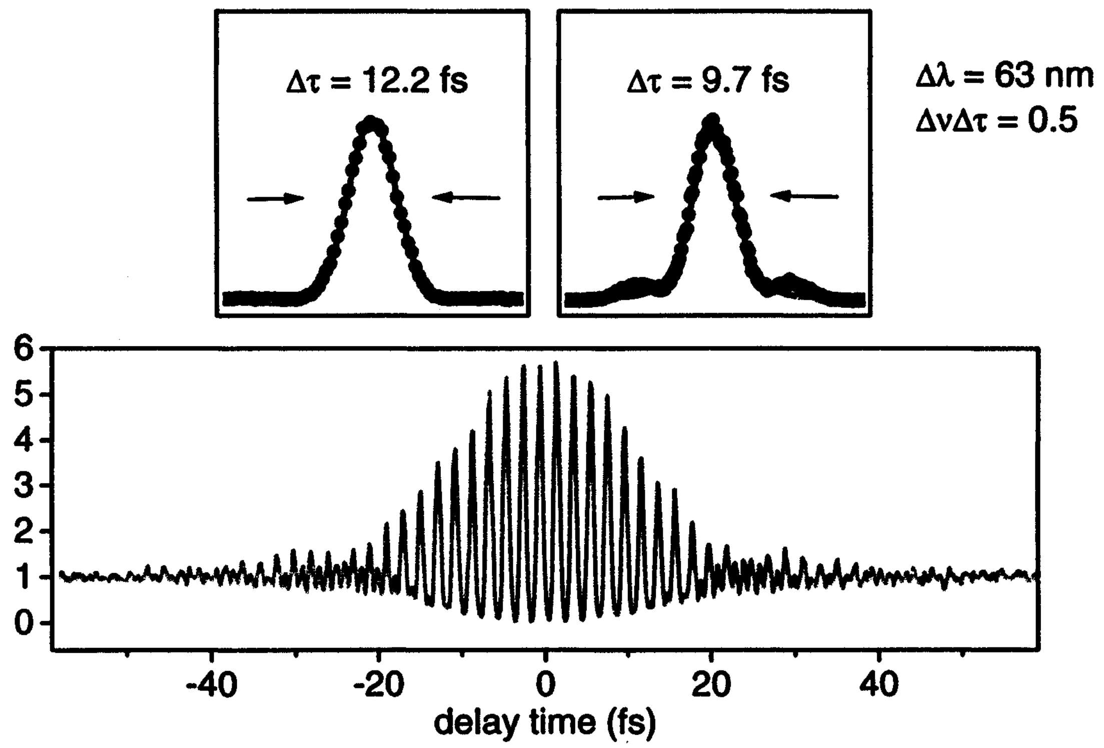
$$A(\tau) = \int_{-\infty}^{\infty} dt \left\{ \mathcal{E}_1^4(t-\tau) + \mathcal{E}_2^4(t) + 4\mathcal{E}_1^2(t-\tau)\mathcal{E}_2^2(t) \right\}$$ "background" + "envelope"

$$\tilde{B}(\tau) = \int_{-\infty}^{\infty} dt \left\{ \mathcal{E}_1(t-\tau)\mathcal{E}_2(t) \left[ \mathcal{E}_1^2(t-\tau) + \mathcal{E}_2^2(t) \right] e^{i[\varphi_1(t-\tau) - \varphi_2(t)]} \right\}$$ "fringes"

$$\tilde{C}(\tau) = \int_{-\infty}^{\infty} dt \left\{ \mathcal{E}_1^2(t-\tau) \cdot \mathcal{E}_2^2(t) \cdot e^{2i[\varphi_1(t-\tau) - \varphi_2(t)]} \right\}$$ "higher order terms"

**interferometric autocorrelation / fringe resolved**

**10 fs pulses at 630 nm**



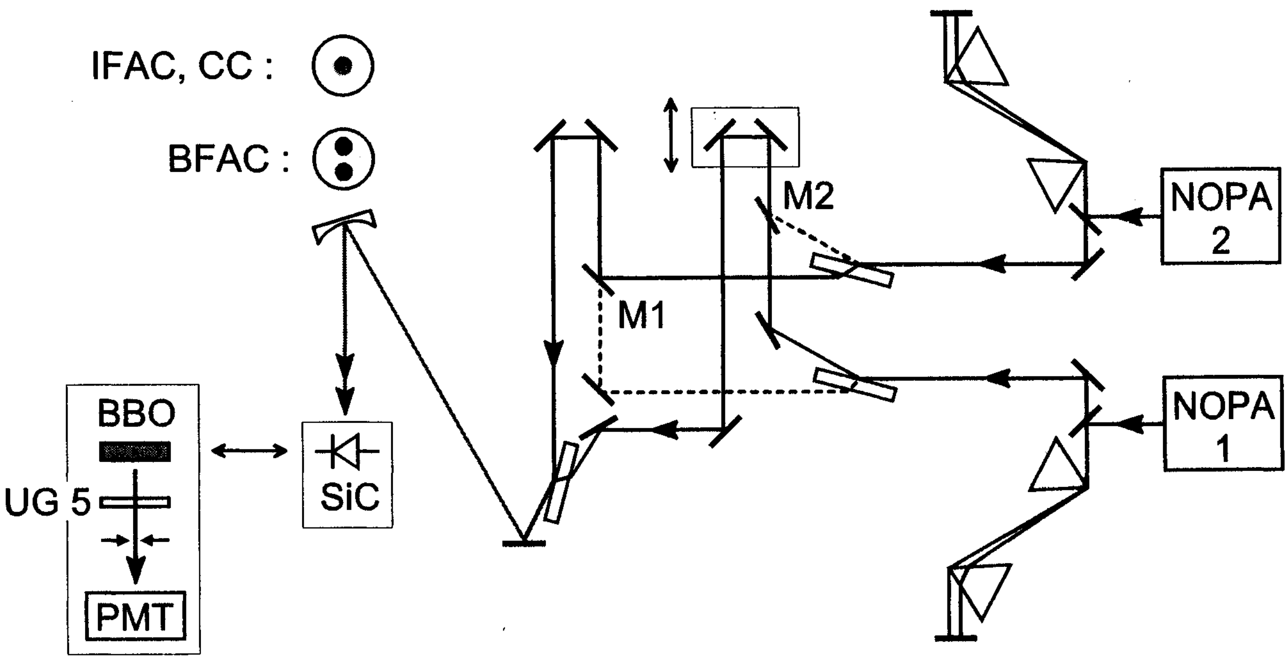
# Pulse Characterization by Photodiodes

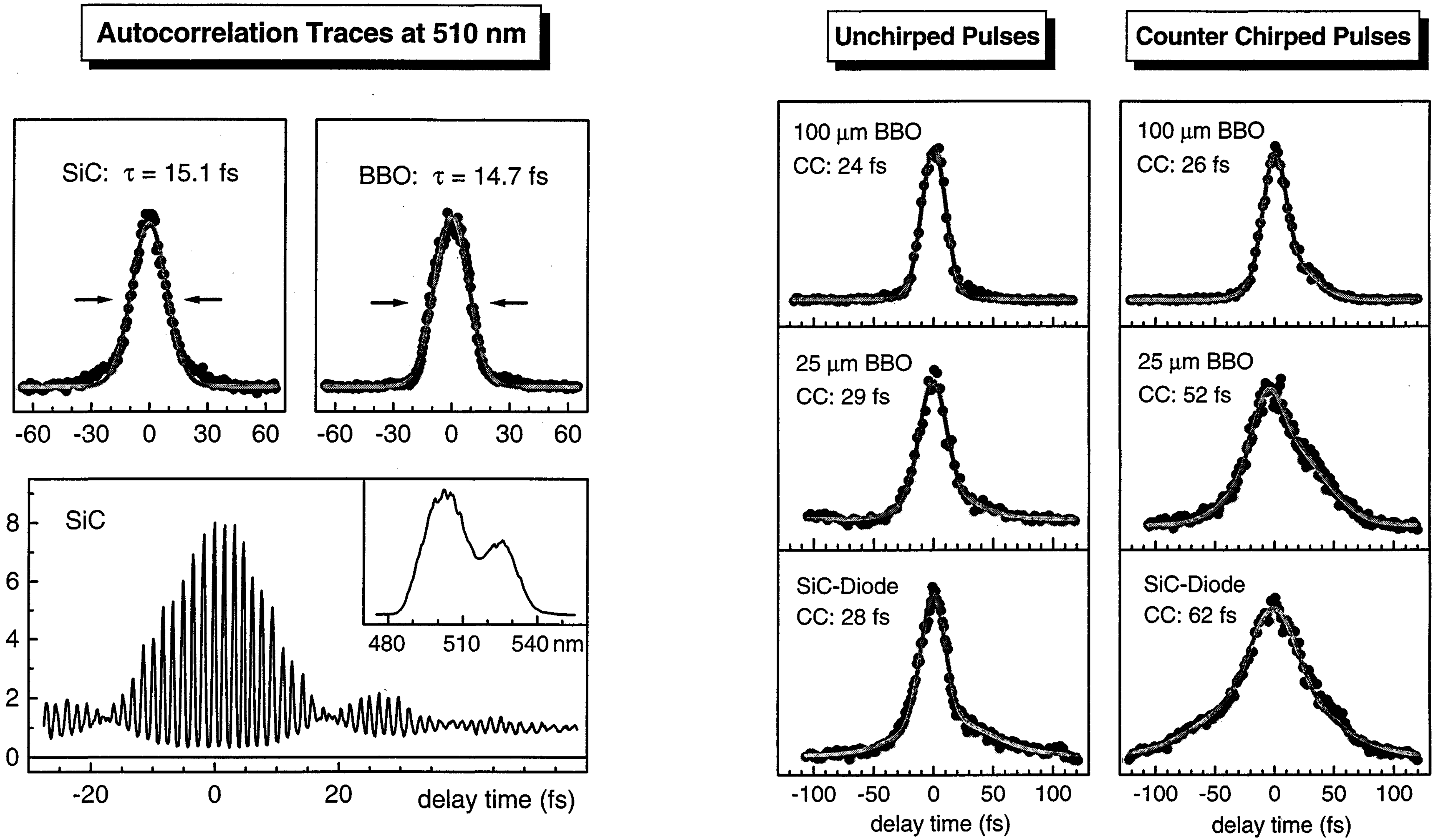
- AlGaAs LED: quadratic dependence at 800 nm, AC of 80 fs-pulses
  D. T. Reid, M. Padgett, C. McGowan, W. E. Sleat, and W. Sibbett, Opt. Lett. **22**, 233 (1997)
- GaAsP photodiode: quadratic dependence at 800 nm, AC of 6 fs-pulses
  J. K. Ranka, A. L. Gaeta, A. Baltuska, M. S. Pshenichnikov, D. A. Wiersma, Opt. Lett. **22**, 1345 (1997)
- SiC photodiode: quadratic dependence at 497 nm, AC of 90 and 480 fs-pulses
  T. Feurer, A. Glass, R. Sauerbrey, Appl. Phys. B. **65**, 295 (1997)

**Advantages :**

- no phase matching ⇒ no angle tuning, broad acceptance bandwidth
- no polarization dependence
- no photomultiplier needed
- robust and compact
- readily available and inexpensive

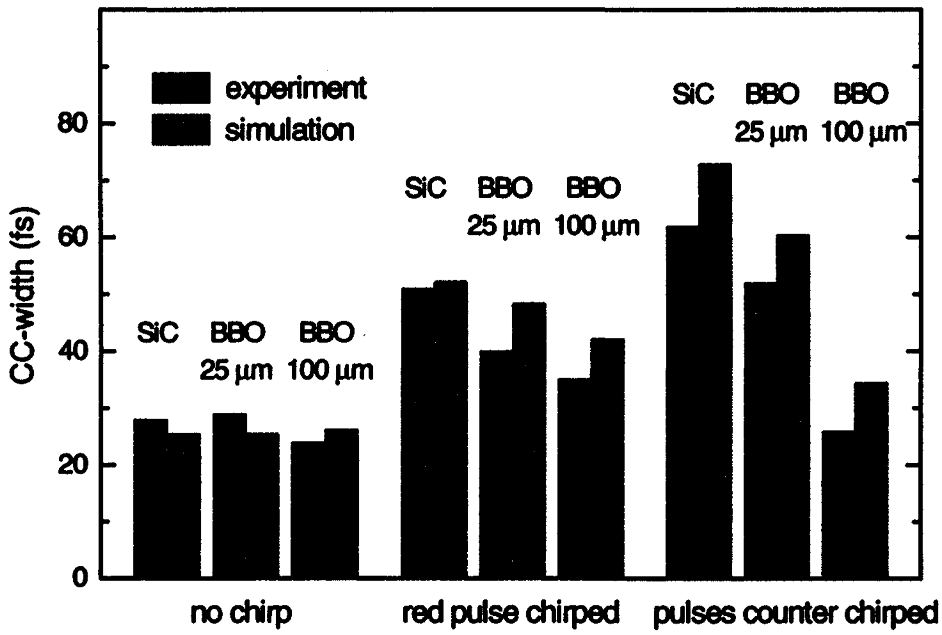
# Experimental Setup




Autocorrelation Traces at 510 nm
SiC: τ = 15.1 fs
BBO: τ = 14.7 fs
-60 -30 0 30 60
-60 -30 0 30 60
SiC
8
6
4
2
0
-20 0 20 delay time (fs)
480 510 540 nm
Unchirped Pulses
Counter Chirped Pulses
100 µm BBO
CC: 24 fs
100 µm BBO
CC: 26 fs
25 µm BBO
CC: 29 fs
25 µm BBO
CC: 52 fs
SiC-Diode
CC: 28 fs
SiC-Diode
CC: 62 fs
-100 -50 0 50 100
delay time (fs)
-100 -50 0 50 100
delay time (fs)

$$I_{SF}(\omega_{SF},\tau) \propto \left| \int \tilde{E}_1(\omega_{SF}-\omega)\tilde{E}_2(\omega)\exp(i\omega\tau)\exp\left(i\frac{\Delta kL}{2}\right)\mathrm{sinc}\left(\frac{\Delta kL}{2}\right)d\omega \right|^2 \ {}^{*}$$

$$I_{CC}(\tau) = \int I_{SF}(\omega_{SF},\tau)\, d\omega_{SF}$$

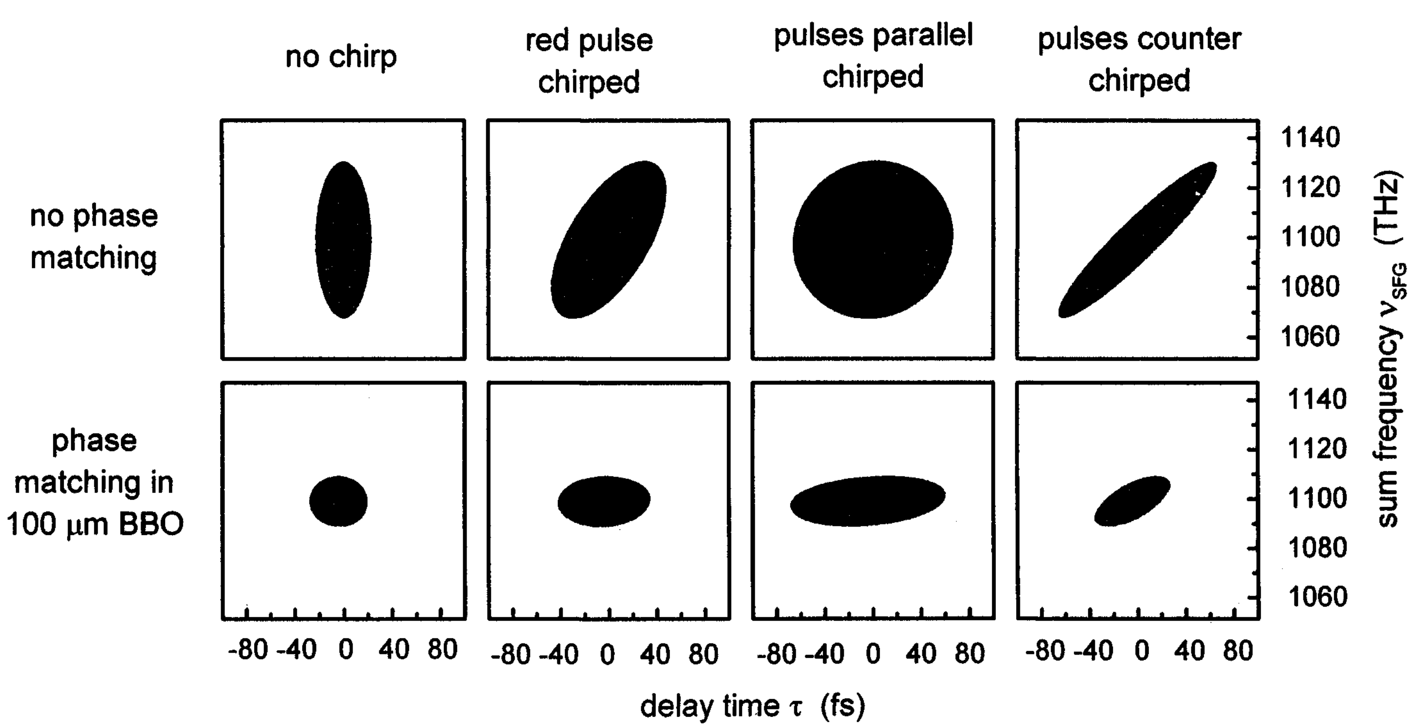



Gaussian pulses:
$\Delta t$ = 18 fs

Chirp:
1.9 fs / THz at 600 nm
-2.1 fs / THz at 500 nm

* A. M. Weiner, IEEE J. Quantum Electron. 19, 1276 (1983), SVA-appr.

## Frequency Resolved Sum Frequency Signal

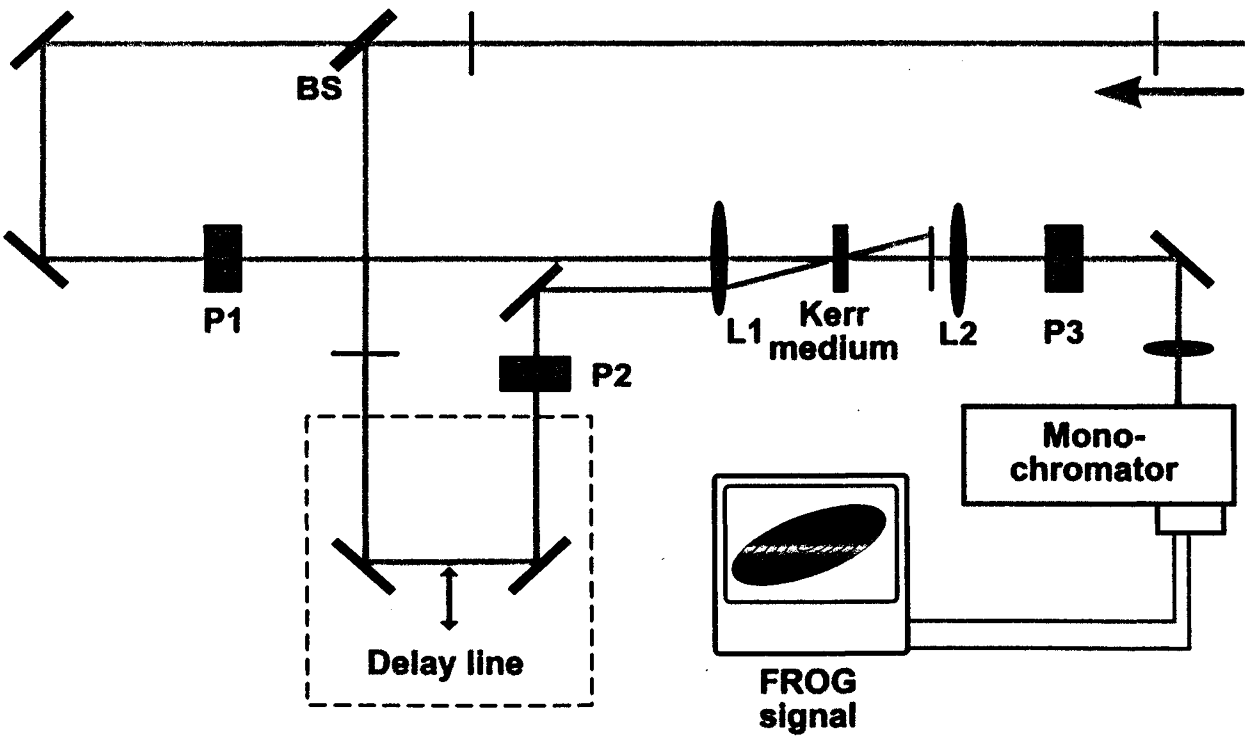


## Conclusions

- Bandwidth limitation of ≤ 100 μm nonlinear crystals can result in observed crosscorrelations much shorter than the real ones
- Reliable and simple auto- and crosscorrelation measurements of sub-20 fs visible pulses in SiC photodiodes (two-photon conductivity)
- Crosscorrelation at the sample position of the spectroscopic experiment

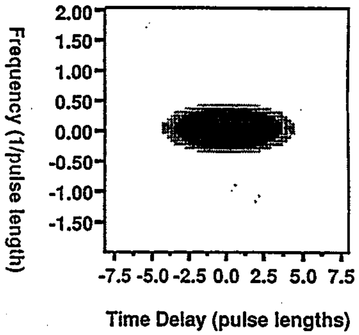
S. Lochbrunner, P. Huppmann, and E. Riedle
Crosscorrelation measurements of ultrashort visible pulses: comparison between nonlinear crystals and SiC photodiodes
Opt. Commun. **184**, 321-328 (2000)

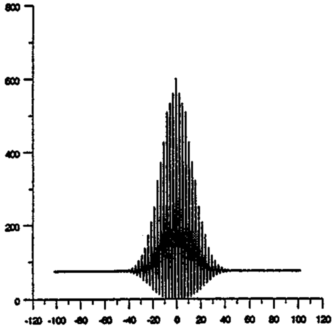
## Frequency Resolved Optical Gating
## Schematic setup for Kerr (polarization) FROG



# FREQUENCY-RESOLVED OPTICAL GATING (FROG)

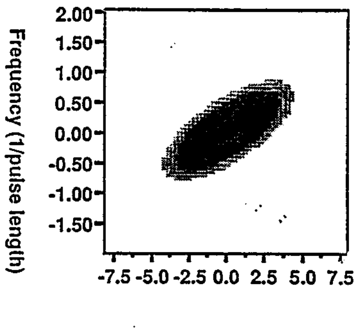
## Transform-Limited = No Chirp

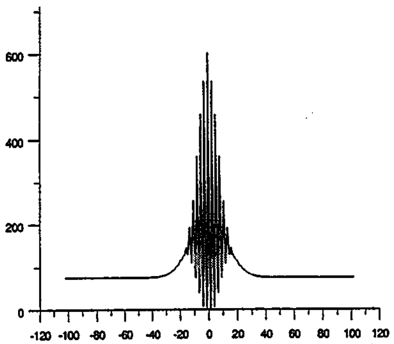


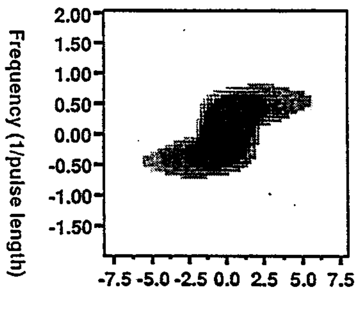
K.W. DeLong,
D.J. Kane,
R. Trebino
(Sandia National Laboratories, Livermore,CA)

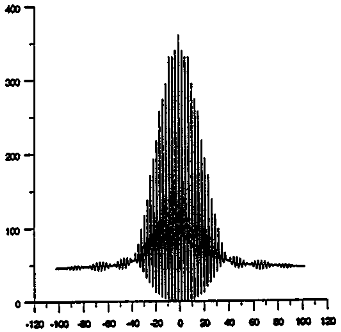
## Linear Chirp = Quadratic Phase

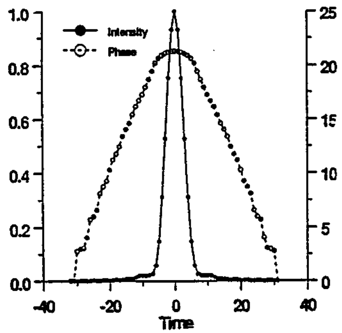


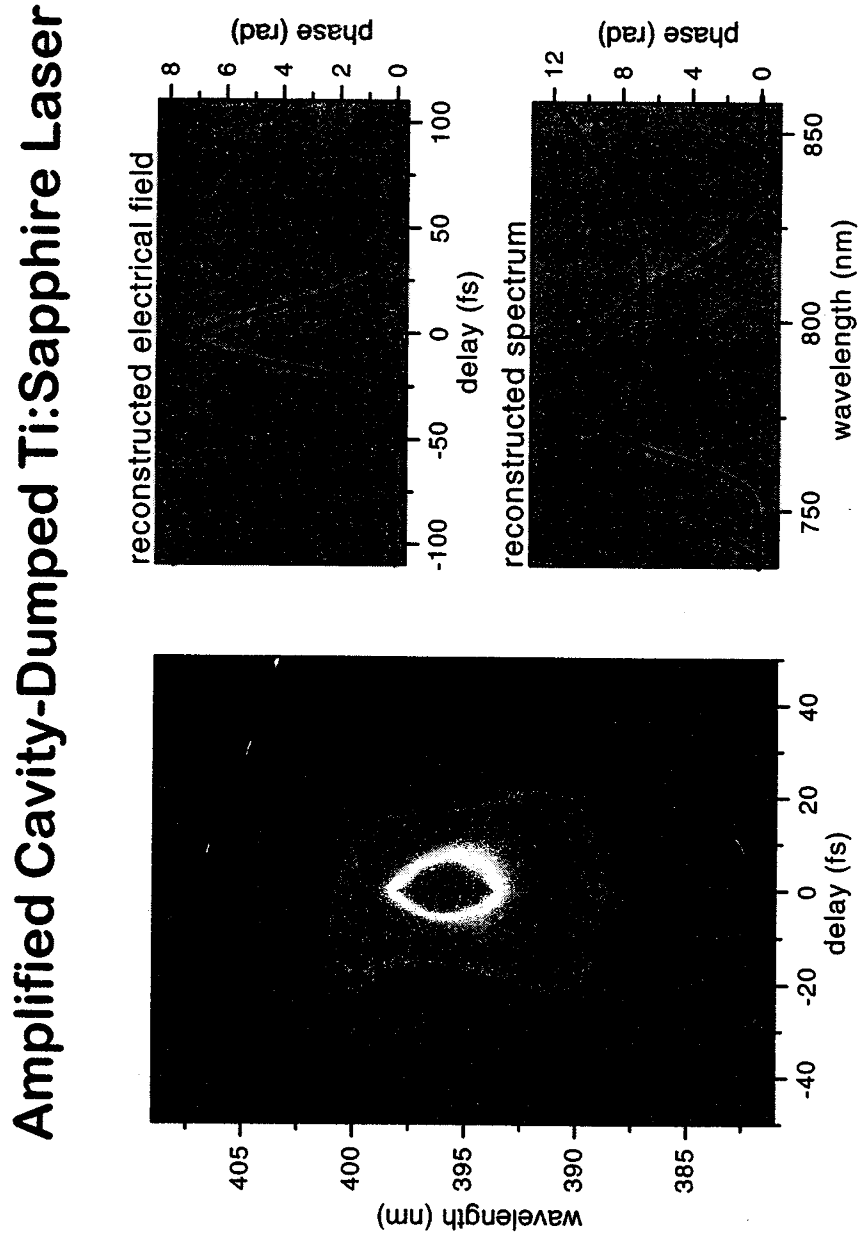



## Spectral Quartic Phase



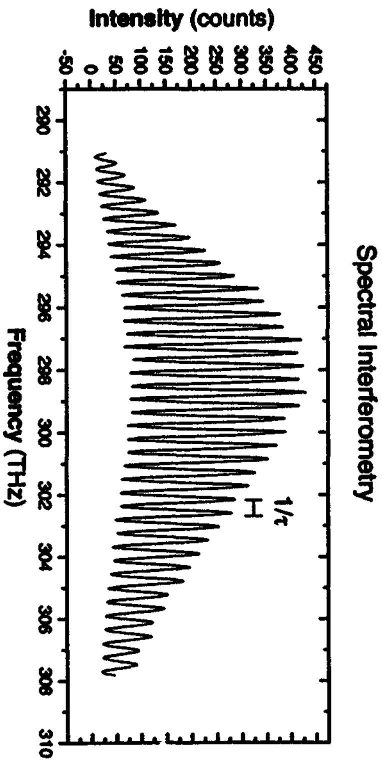


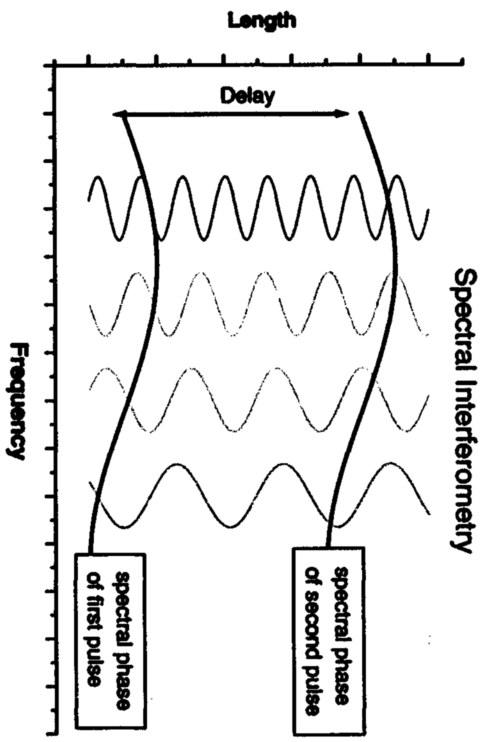



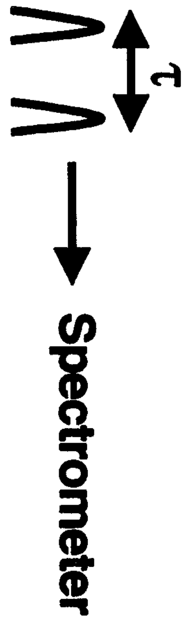
# Characterisation of Laser Pulses with SPIDER

(Spectral Phase Interferometry for Direct Electric-Field Reconstruction)

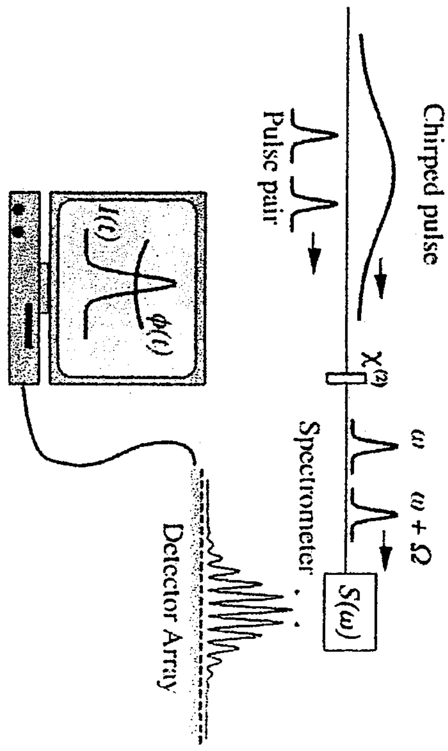
- ***Principle***
- ***Experimental Setup***
- ***Results***
- ***Conclusion***



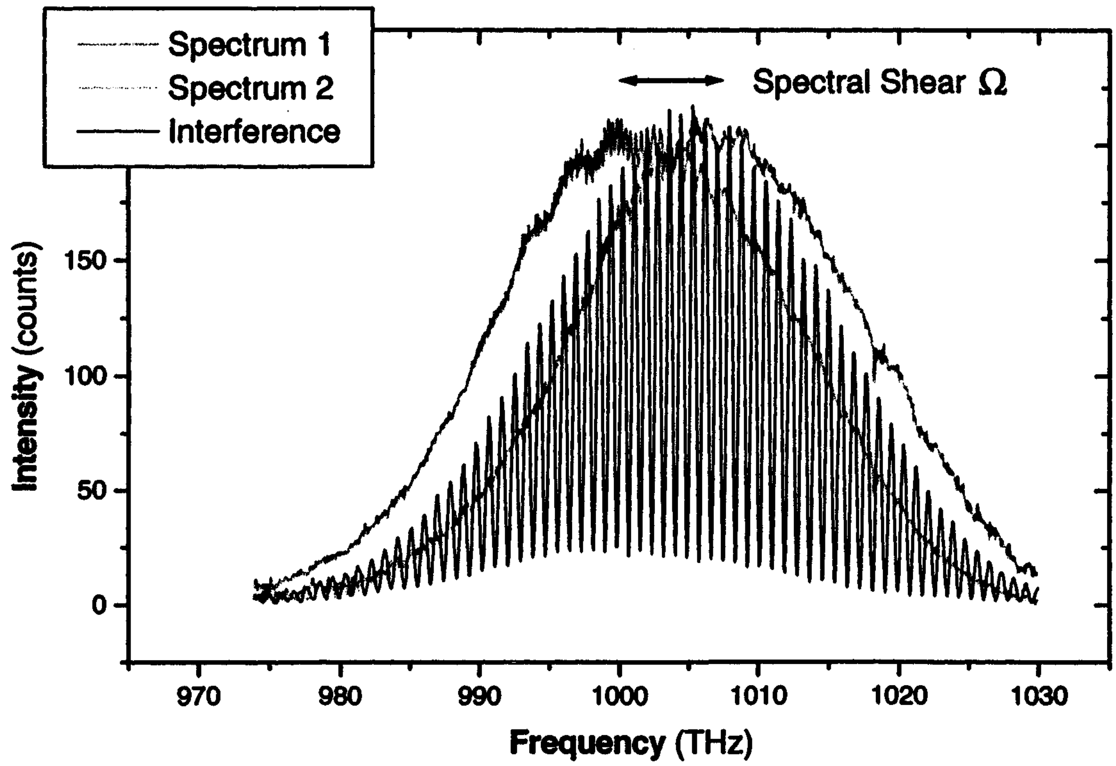
## Spectral Phase Interferometry for Direct Electric-Field Reconstruction

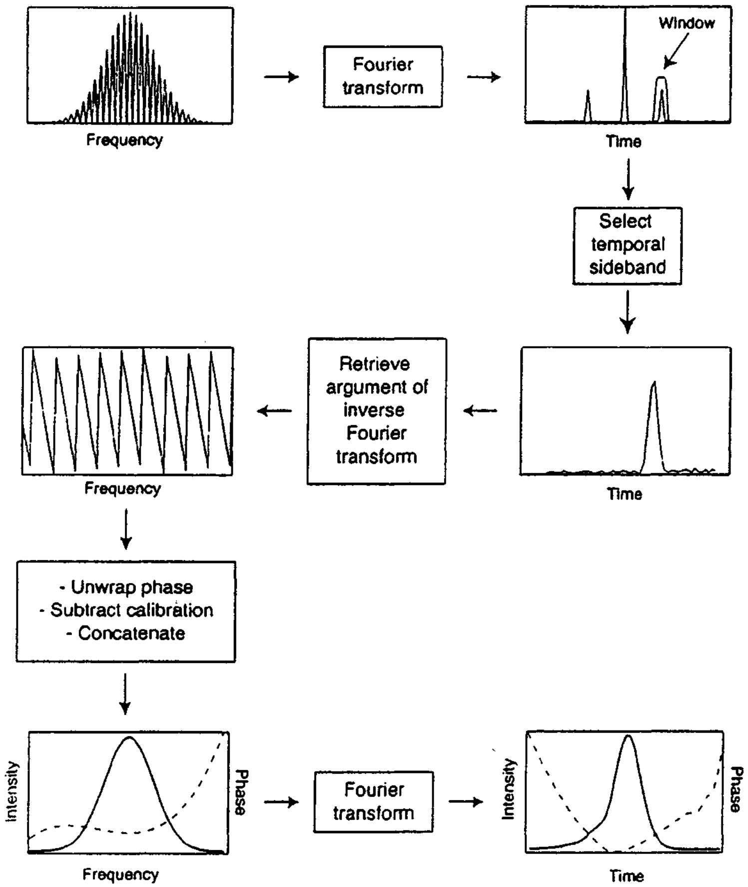



$$S(\omega) = I(\omega) + I(\omega+\Omega) + 2\sqrt{I(\omega)I(\omega+\Omega)} \times \cos\{\phi(\omega+\Omega) - \phi(\omega) + \omega\tau\},$$

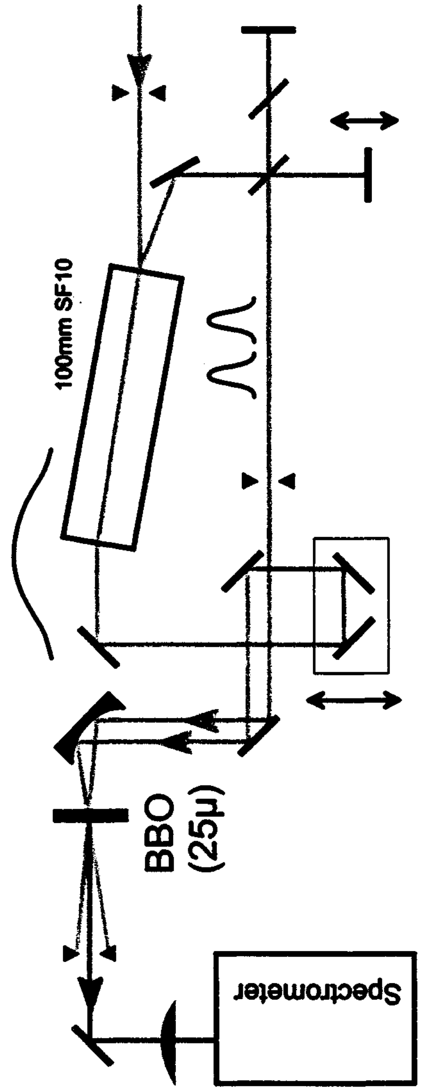
C. Iaconis and I. A. Walmsley, Opt. Lett. **23** (1998), 792

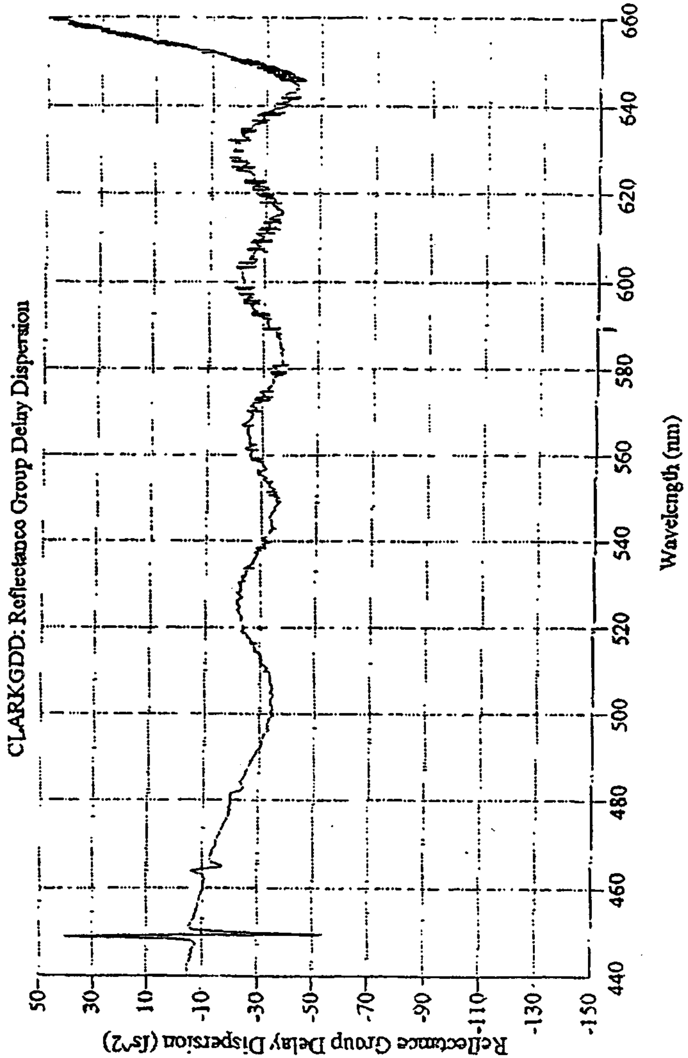
## Spectral Shearing Interferometry

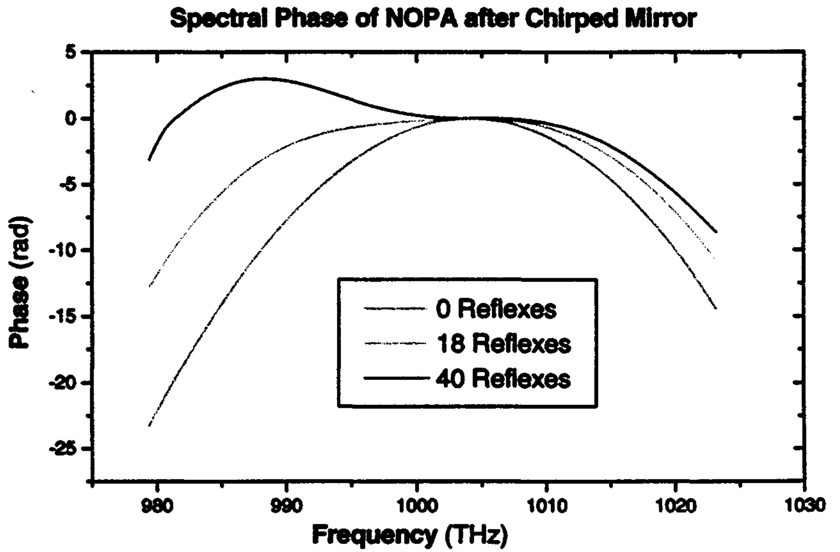


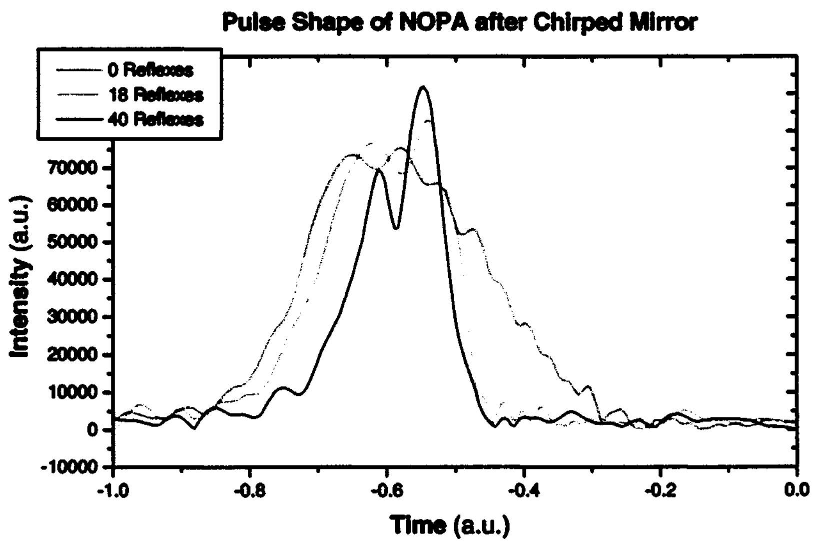



# Experimental Setup




CLARKGDD: Reflectance Group Delay Dispersion
Wavelength (nm)
Reflectance Group Delay Dispersion (fs^2)


Spectral Phase of NOPA after Chirped Mirror
Phase (rad)
Frequency (THz)
0 Reflexes
18 Reflexes
40 Reflexes


Pulse Shape of NOPA after Chirped Mirror
Intensity (a.u.)
Time (a.u.)
0 Reflexes
18 Reflexes
40 Reflexes