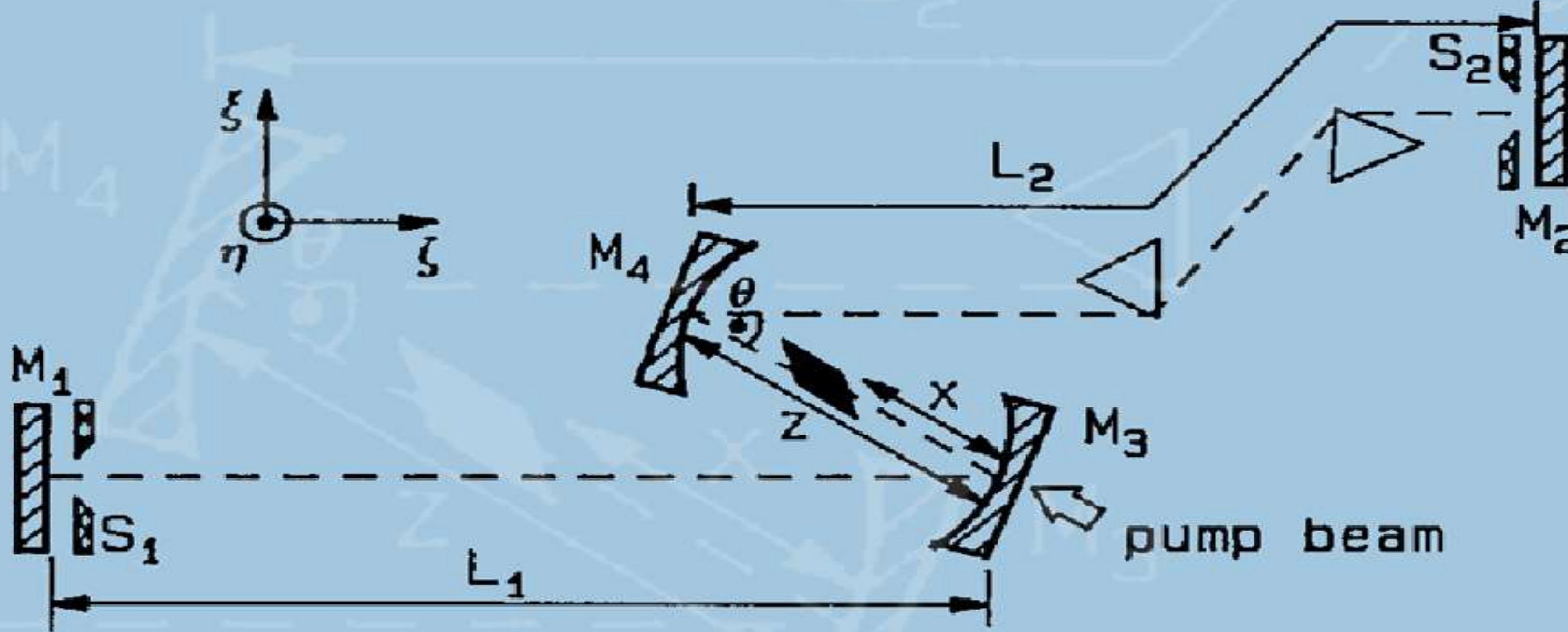
ULTRAFAST OPTICS



by PIOTR WASYLCZYK

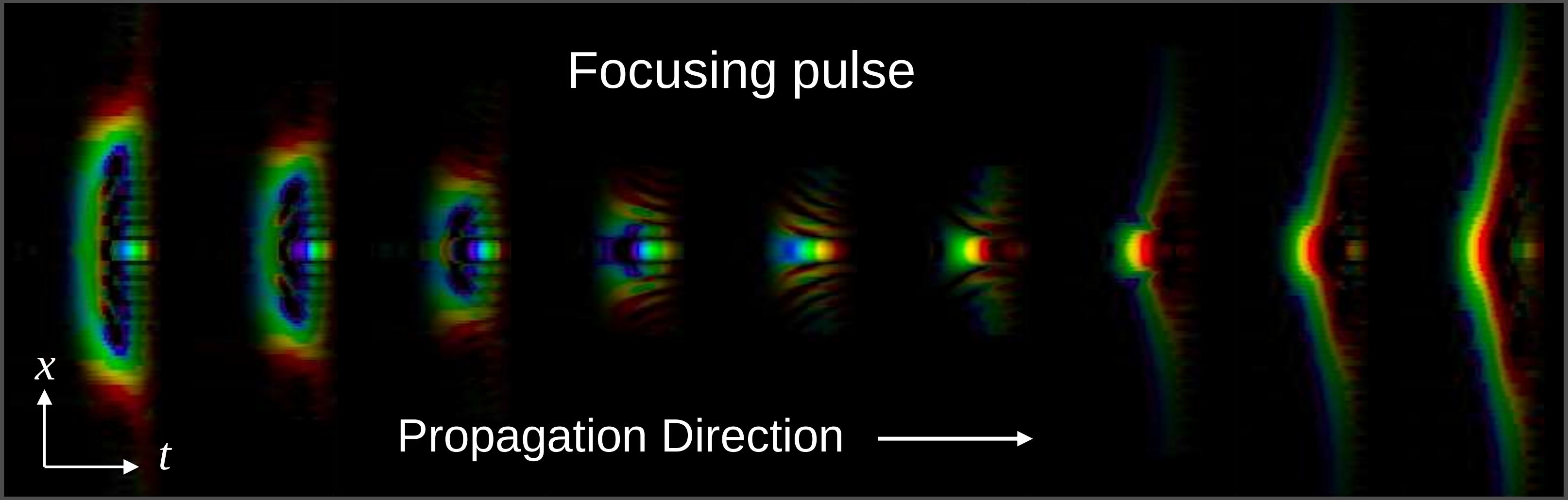
Measuring Ultrashort Laser Pulses III: Interferometric Techniques

Measuring ultraweak ultrashort pulses: Spectral Interferometry

Measuring ultrafast variation of polarization

Spectral interferometry without a reference pulse (SPIDER)

Spatio-temporal measurement of ultrafast light



Sensitivity of FROG

1 microjoule = 10^{-6} J

1 nanojoule = 10^{-9} J

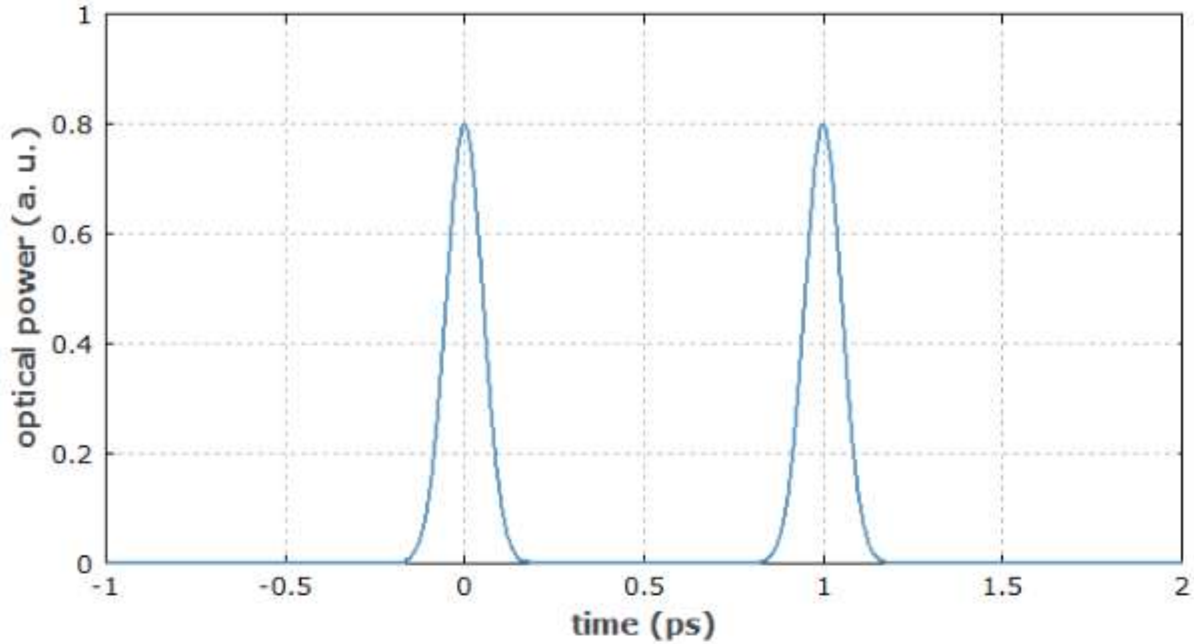
FROG can measure pulses with as little energy as: 1 picojoule = 10^{-12} J

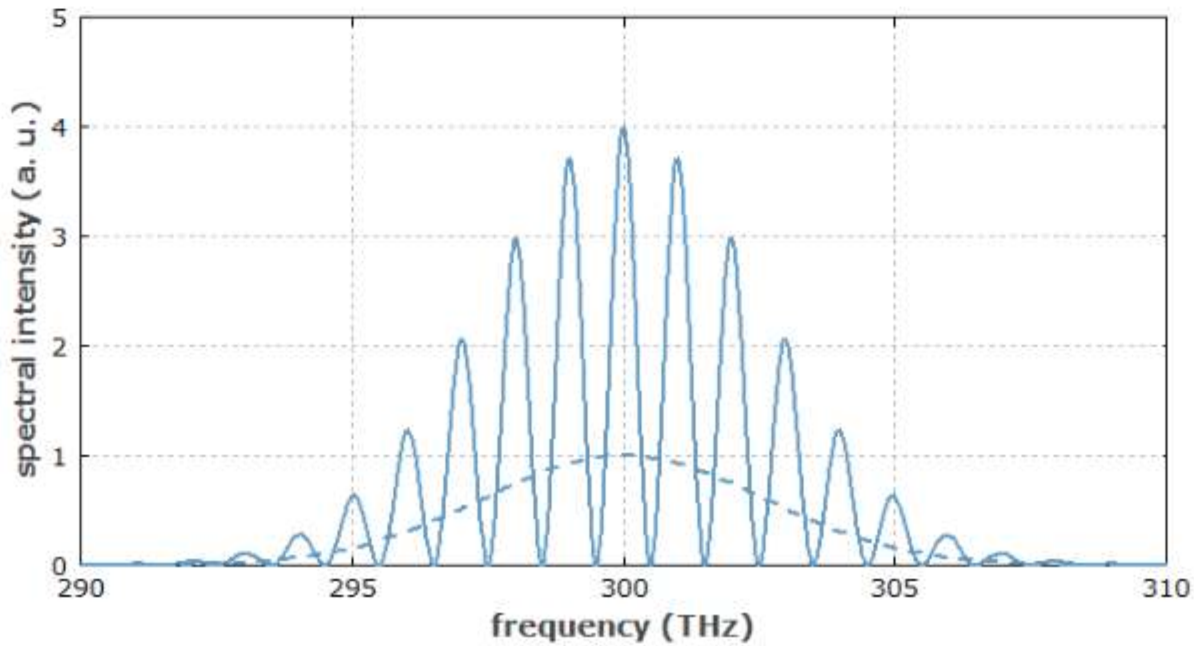
1 femtojoule = 10^{-15} J

1 attojoule = 10^{-18} J

Assumes multi-shot measurement of ~800nm ~100fs pulses at ~100MHz rep rate.

What is the spectrum of two identical short light pulses, delayed in time?





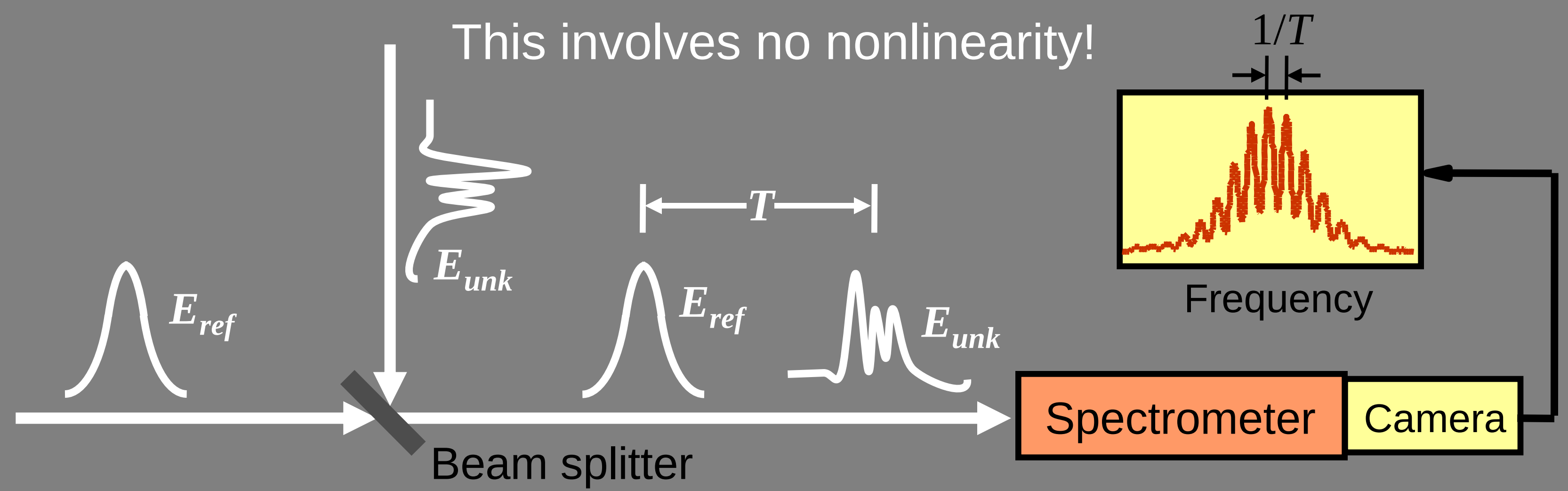
RP Photonics encyclopedia

Spectral Interferometry

Froehly, et al., J. Opt. (Paris) 4, 183 (1973)
Lepetit, et al., JOSA B, 12, 2467 (1995)
Fittinghoff, et al., Opt. Lett., 21, 884 (1996).
C. Dorrer, JOSA B, 16, 1160 (1999)

Measure the spectrum of the sum of a known and unknown pulse.

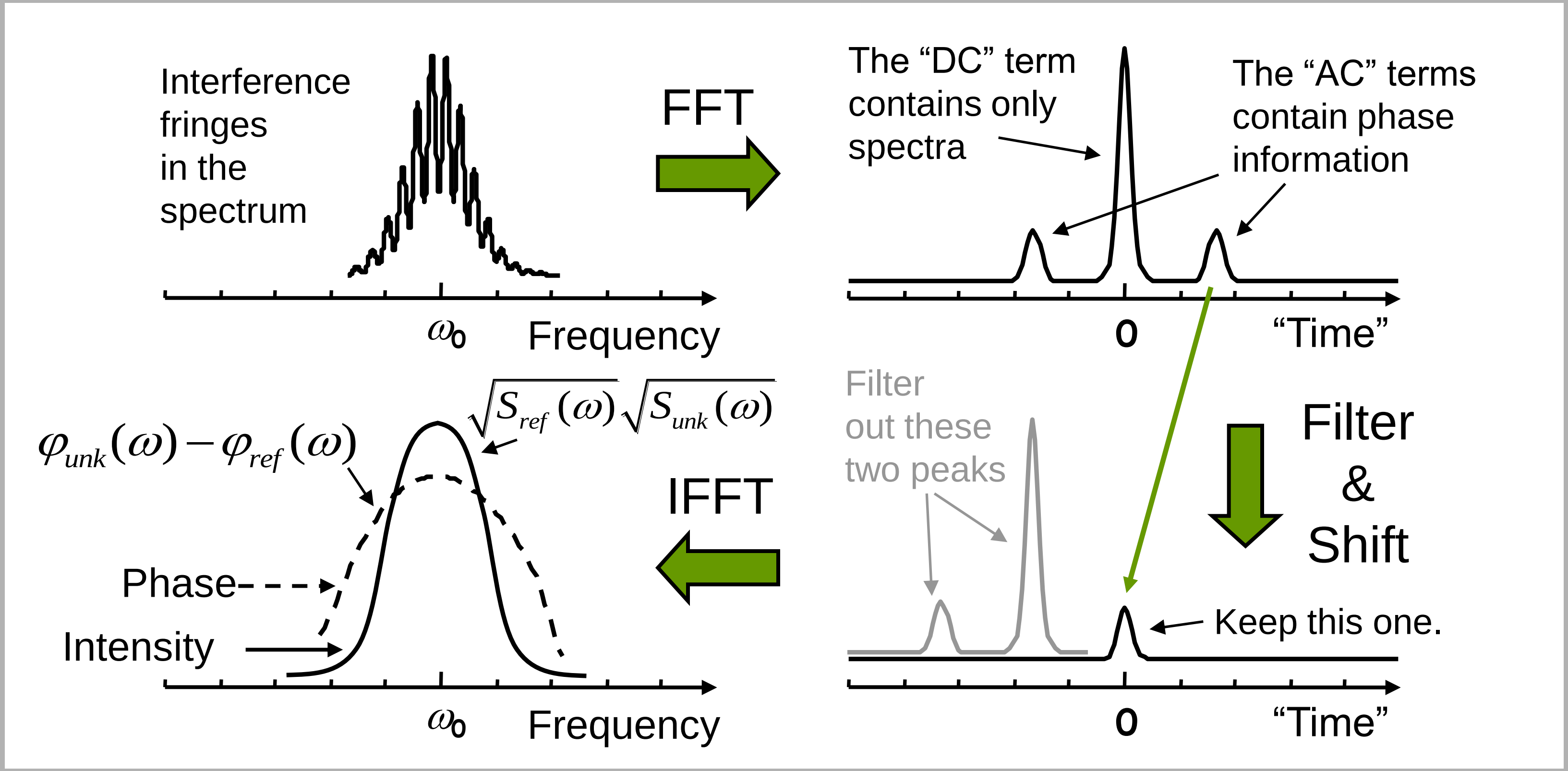
Retrieve the unknown pulse $\tilde{E}(\omega)$ from the cross term.



$$S_{SI}(\omega) = S_{ref}(\omega) + S_{unk}(\omega) + 2\sqrt{S_{ref}(\omega)}\sqrt{S_{unk}(\omega)}\cos[\varphi_{unk}(\omega) - \varphi_{ref}(\omega) + \omega T]$$

With a FROG-measured reference pulse, this technique is known as TADPOLE (Temporal Analysis by Dispersing a Pair Of Light E-fields).

Retrieving the pulse in spectral interferometry

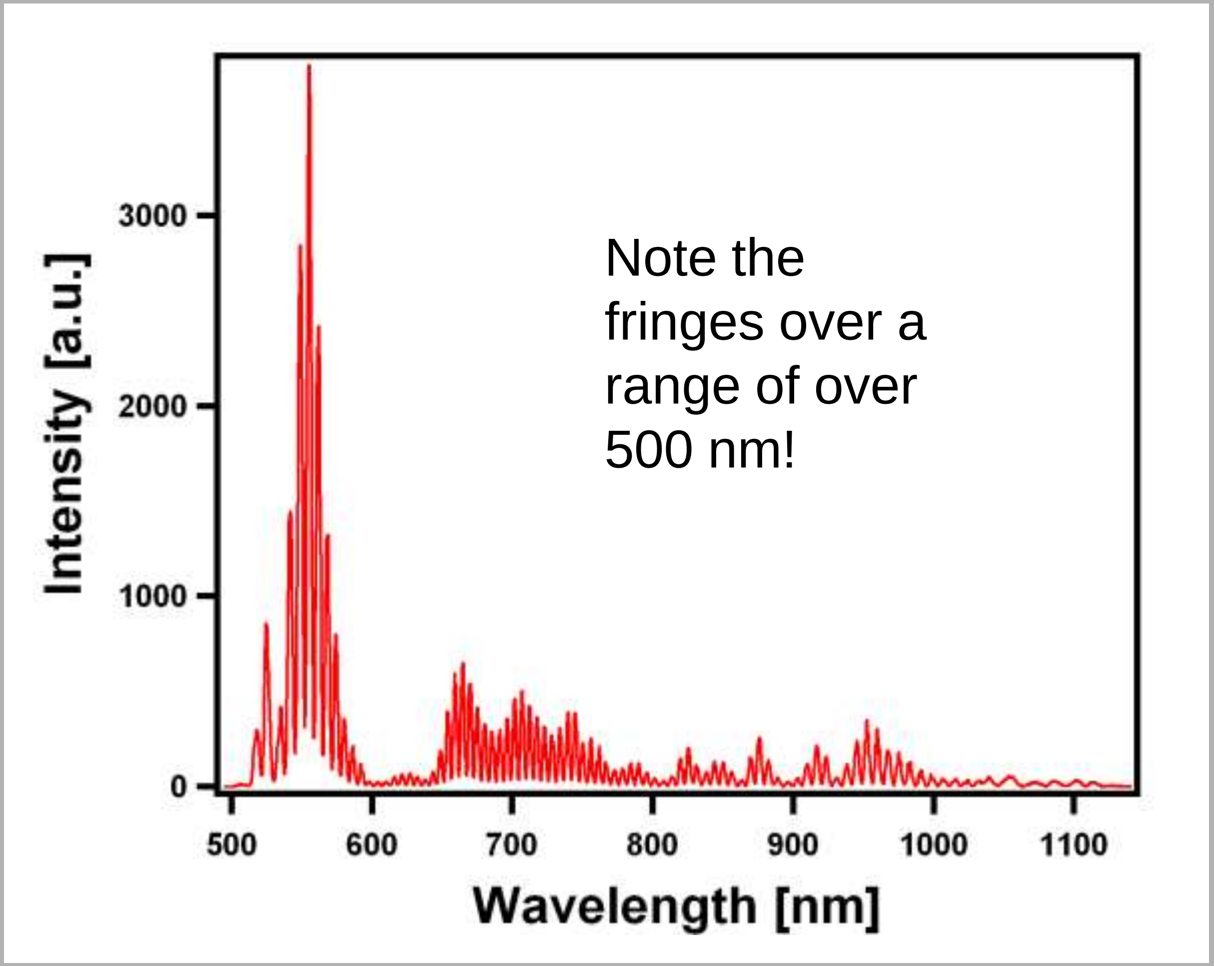


This retrieval algorithm is quick, direct, and reliable.

It essentially uniquely yields the pulse.

Froehly, et al. 1972; Lepetit, et al. 1995; Fittinghoff, et al. 1996.

Spectral interferometry of continuum



Sensitivity of Spectral Interferometry (TADPOLE)

1 microjoule = 10^{-6} J

1 nanojoule = 10^{-9} J

1 picojoule = 10^{-12} J

1 femtojoule = 10^{-15} J

1 attojoule = 10^{-18} J

1 zeptojoule = 10^{-21} J

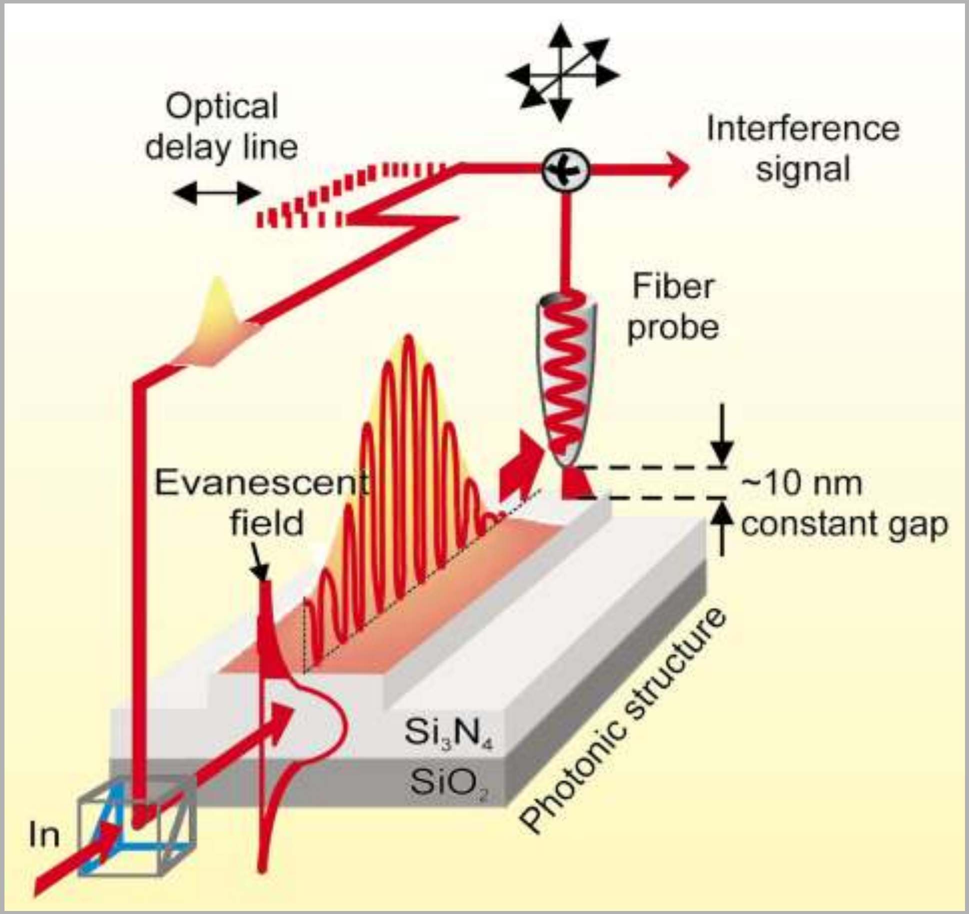
A pulse train containing only 42 zepto-joules (42×10^{-21} J) per pulse has been measured.

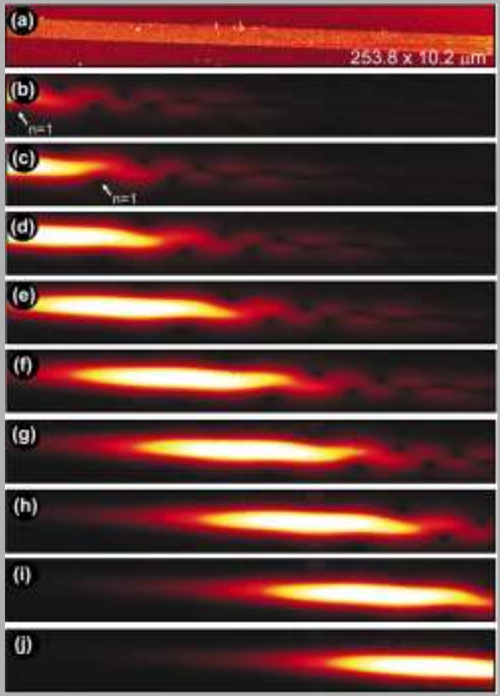
That's one photon every five pulses!

Fittinghoff, et al., Opt. Lett. 21, 884 (1996).

TADPOLE can measure pulses with as little energy as: 1 zeptojoule = 10^{-21} J

Application of spectral interferometry





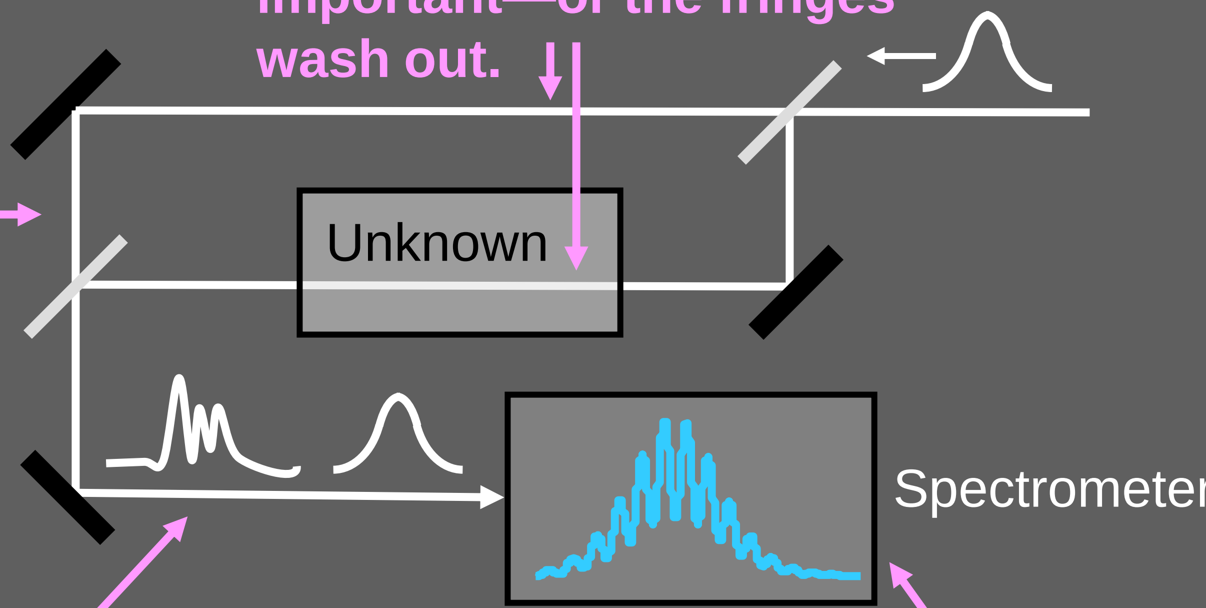
Phase mapping of ultrashort pulses in bimodal photonic structures: A window on local group velocity dispersion
H. Gersen, E. M. H. P. van Dijk, J. P. Korterik, N. F. van Hulst, and L. Kuipers, PHYSICAL REVIEW E **70**, 066609 (2004)

Spectral Interferometry: Experimental Issues

The interferometer is difficult to work with.

Mode-matching is important—or the fringes wash out.

Phase stability is crucial—or the fringes wash out.



Beams must be perfectly collinear—or the fringes wash out.

To resolve the spectral fringes, SI requires at least five times the spectrometer resolution.

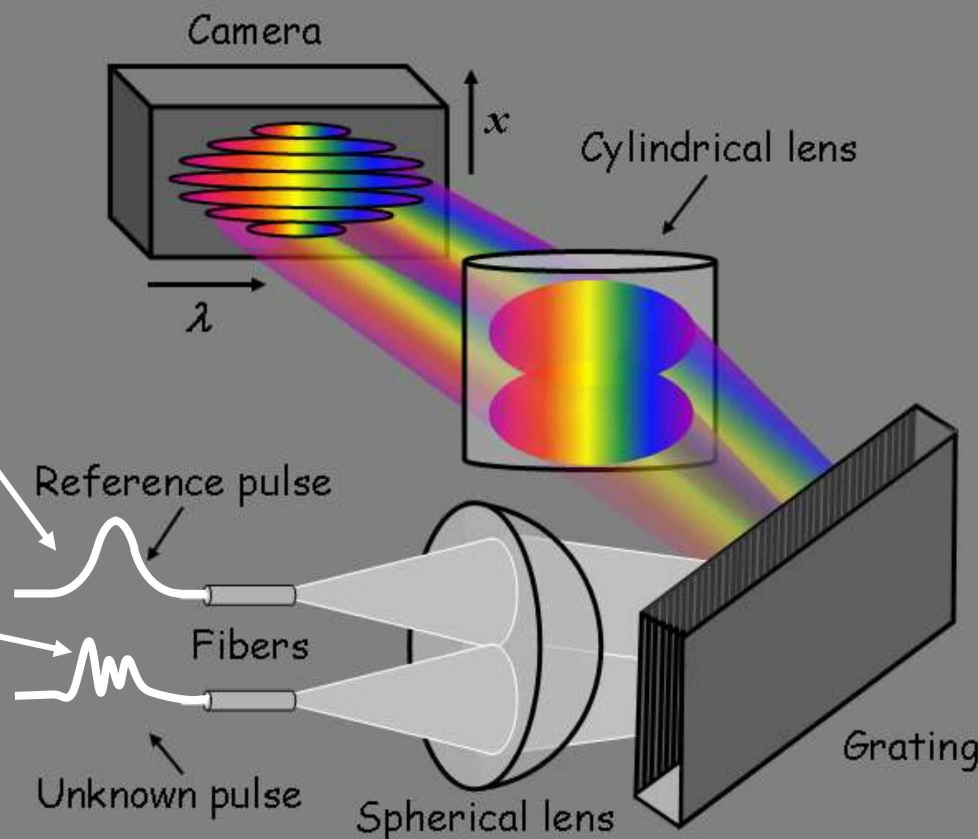
SEA TADPOLE

Spatially Encoded Arrangement (SEA)

SEA TADPOLE uses **spatial,** instead of spectral, fringes.

Fibers maintain alignment.

Single mode fibers assure mode-matching.



Collinearity is not only unnecessary; it's not allowed.

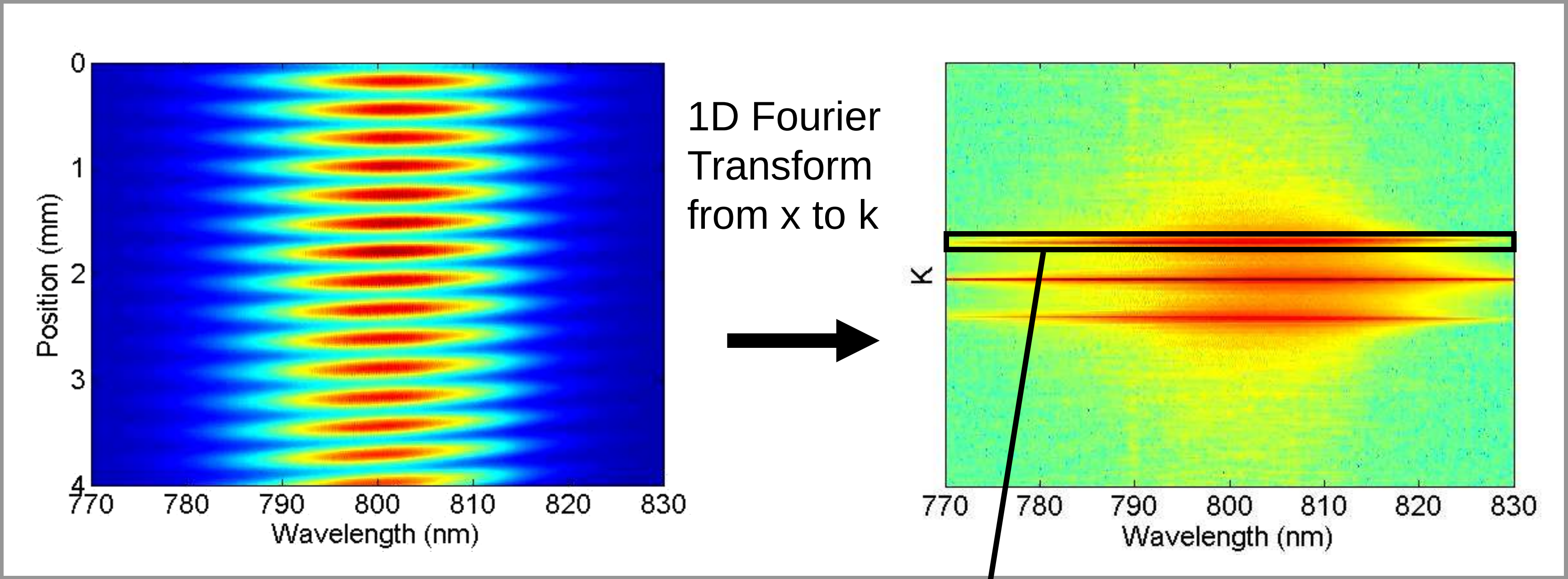
And the crossing angle is irrelevant; it's okay if it varies.

And any and all distortions due to the fibers cancel out!

Retrieve the pulse using spatial fringes, not spectral fringes, with near-zero delay.

The beams cross, so the relative delay, T, varies with position, x.

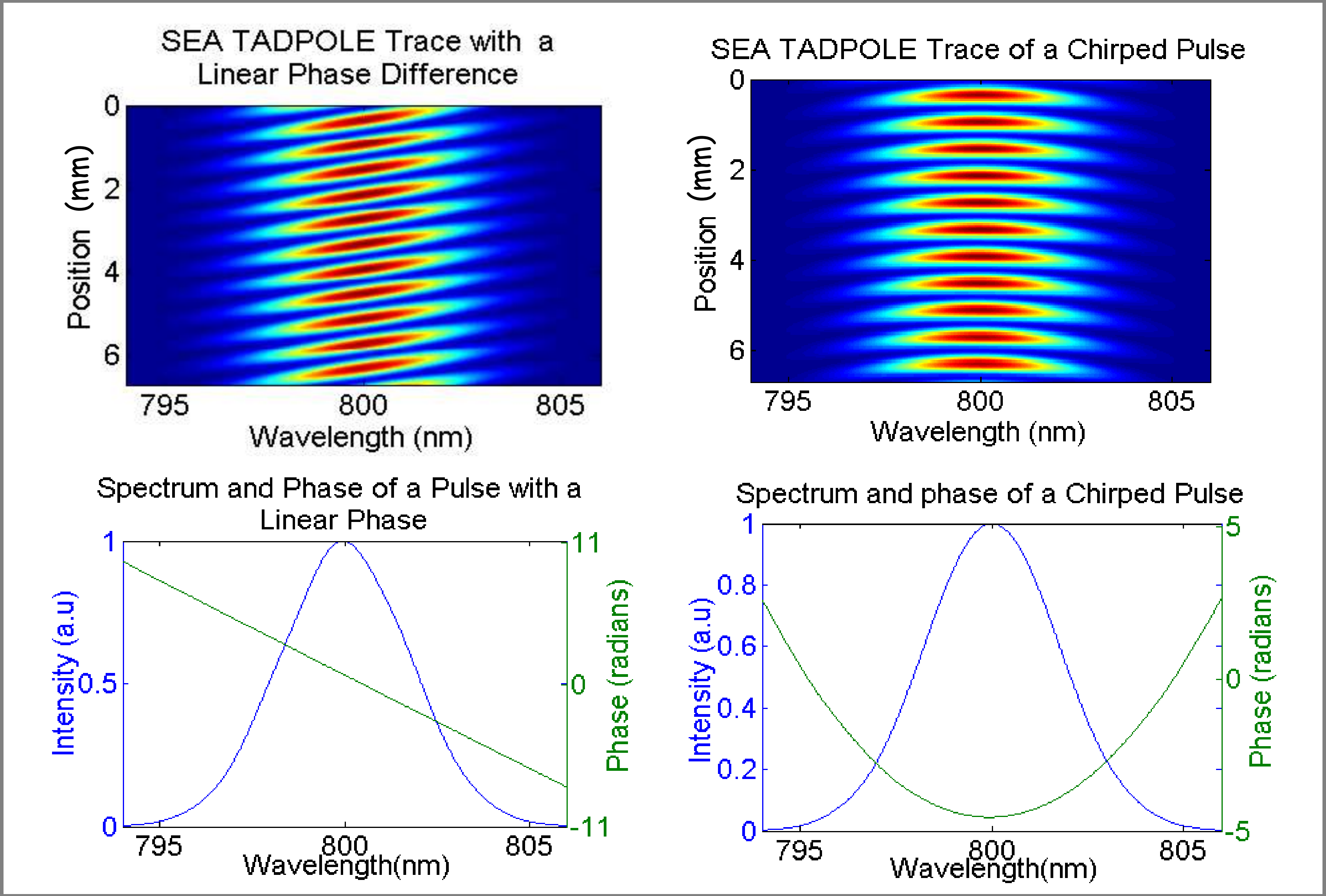
$$S(\omega, x) = S_{ref}(\omega) + S_{unk}(\omega) + 2\sqrt{S_{ref}(\omega)}\sqrt{S_{unk}(\omega)}\cos\left[\varphi_{unk}(\omega) - \varphi_{ref}(\omega) + 2kx\sin\theta\right]$$



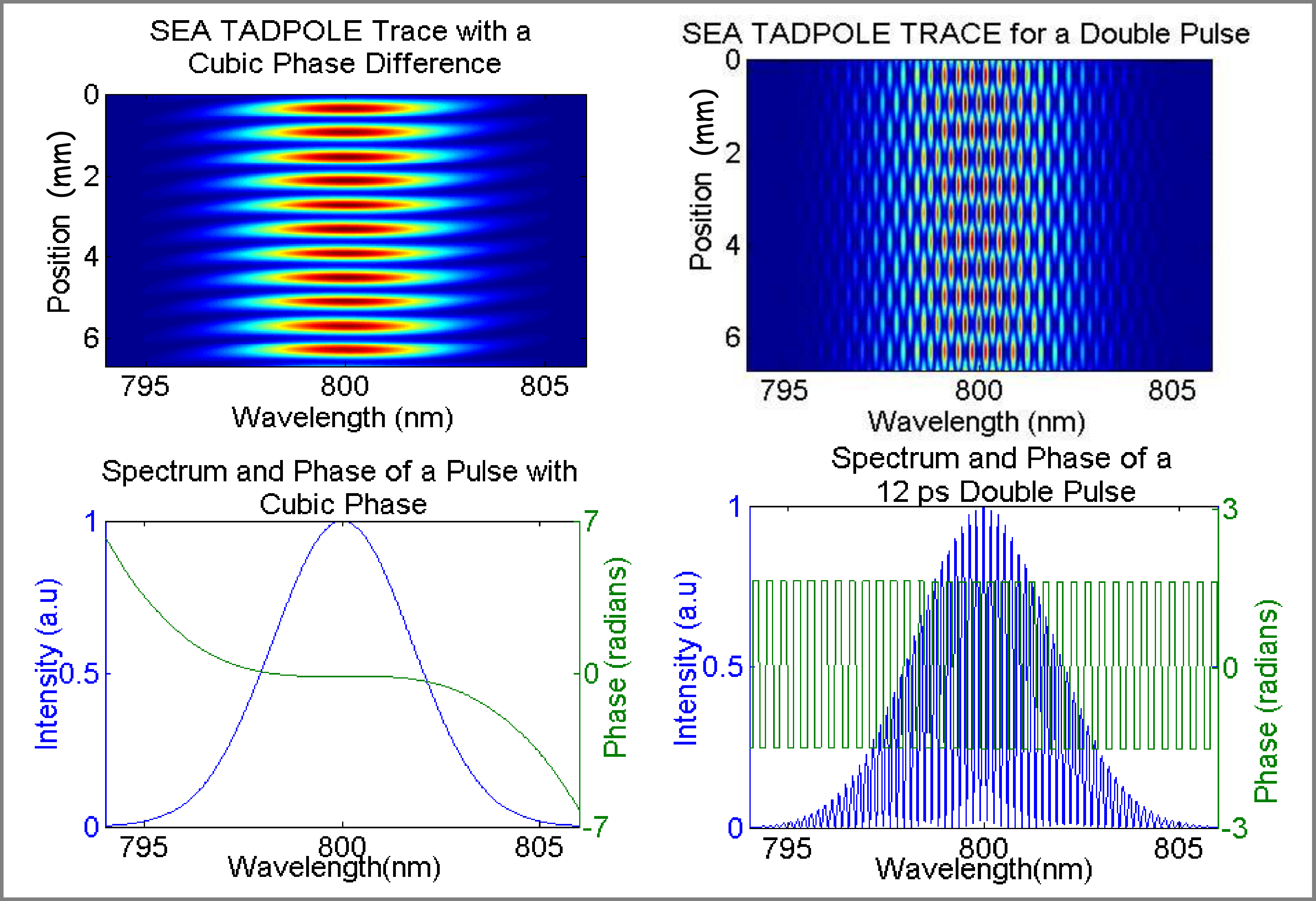
$$\sqrt{S_{ref}(\omega)}\sqrt{S_{unk}(\omega)}\exp\left[-i\left(\varphi_{ref}(\omega) - \varphi_{unk}(\omega)\right)\right]$$

The delay is ~ zero, so this uses the full available spectral resolution!

SEA TADPOLE theoretical traces

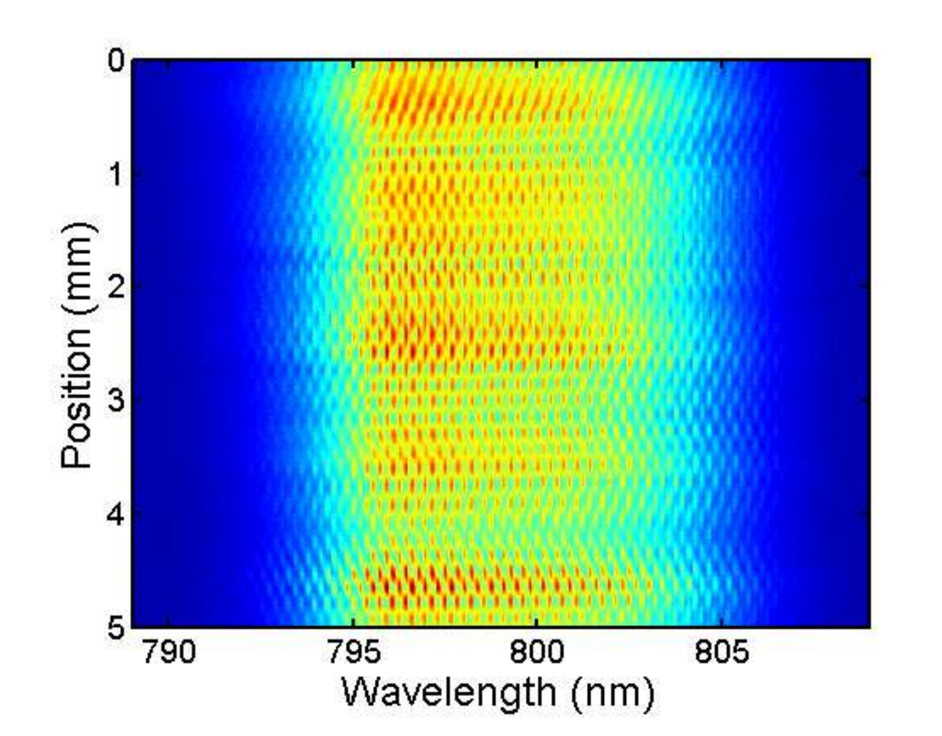


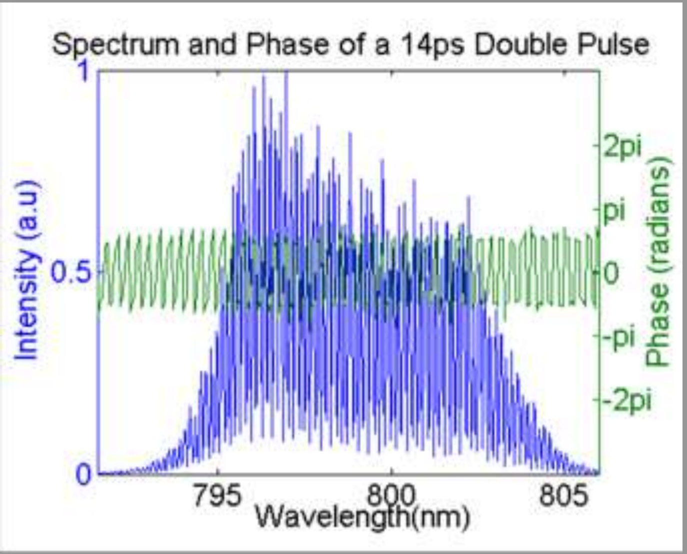
More SEA TADPOLE theoretical traces

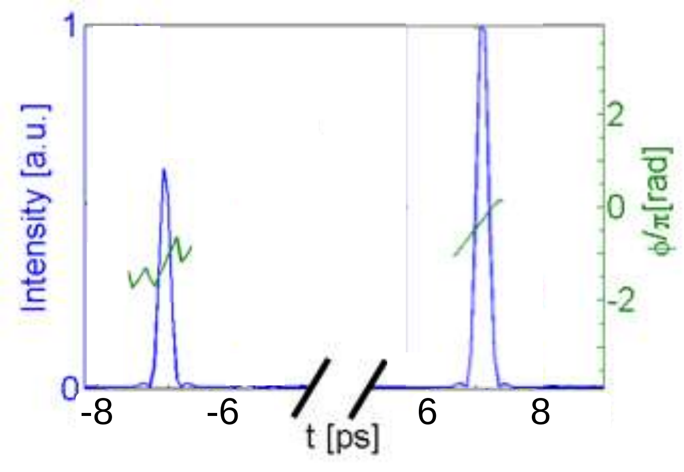


SEA TADPOLE measurements

SEA TADPOLE has enough spectral resolution to measure a 14-ps double pulse.

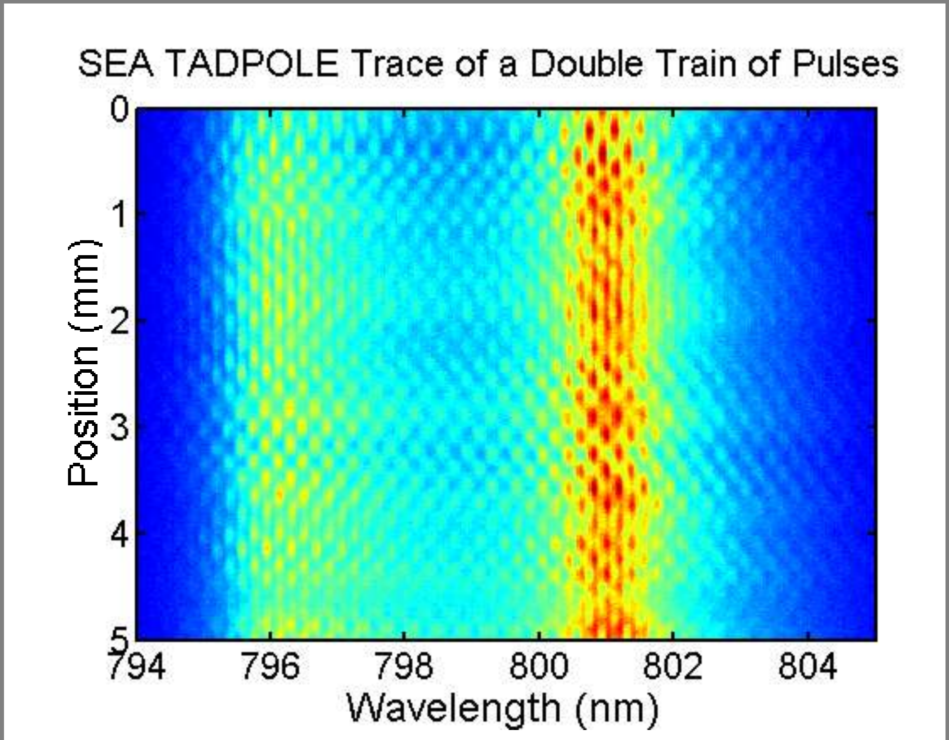


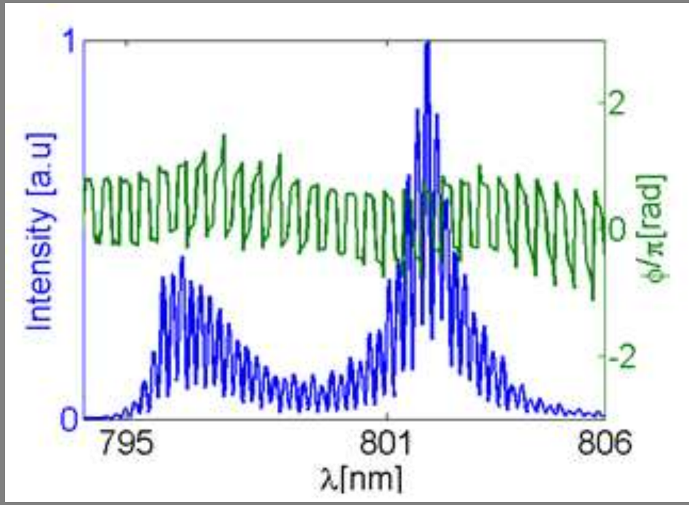


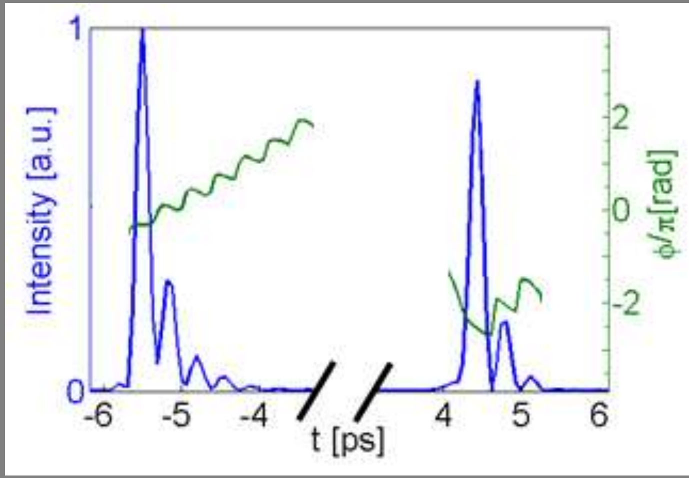


An even more complex pulse…

An etalon inside a Michelson interferometer yields a double train of pulses, and SEA TADPOLE can measure it, too.

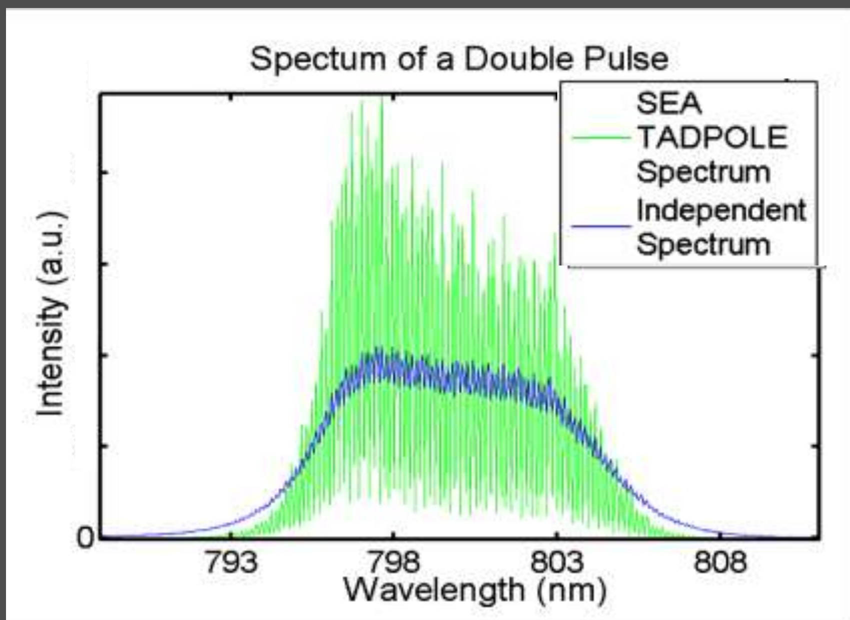


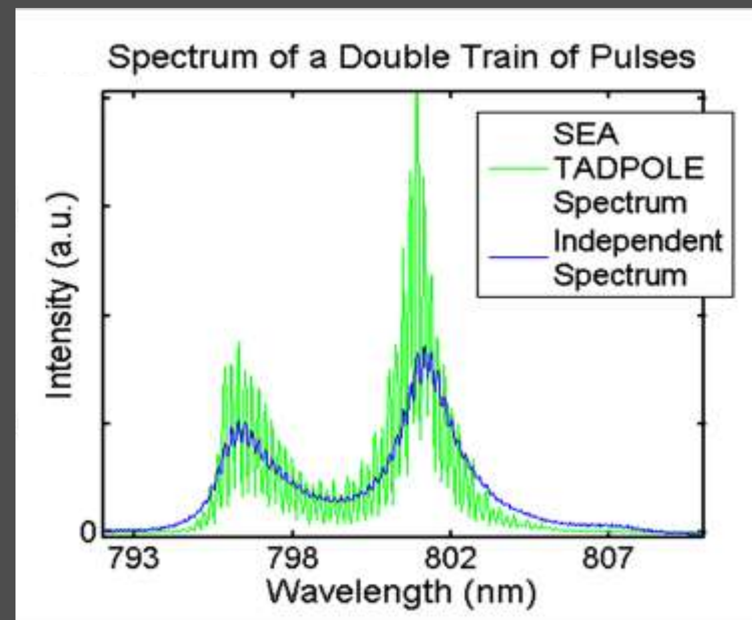




SEA TADPOLE achieves spectral super-resolution!

Blocking the reference beam yields an independent measurement of the spectrum using the same spectrometer.

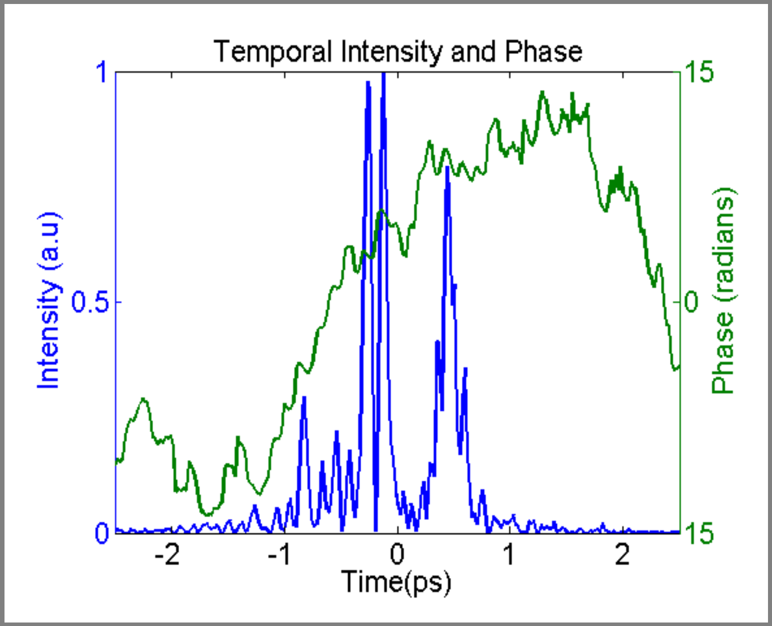


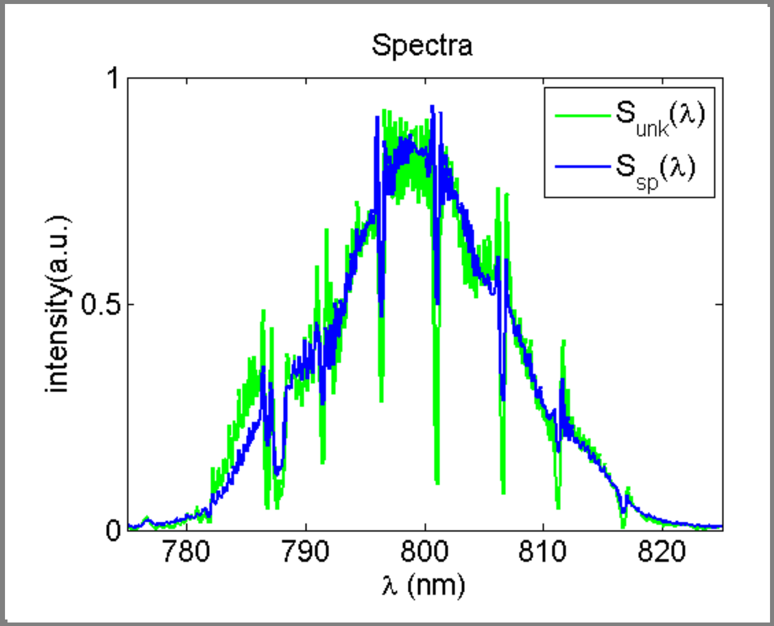


The SEA TADPOLE cross term is essentially the unknown-pulse complex **electric field**. This **goes negative** and so may not broaden under convolution with the spectrometer point-spread function.

SEA TADPOLE for a complex shaped pulse

A complex pulse, generated using a pulse shaper



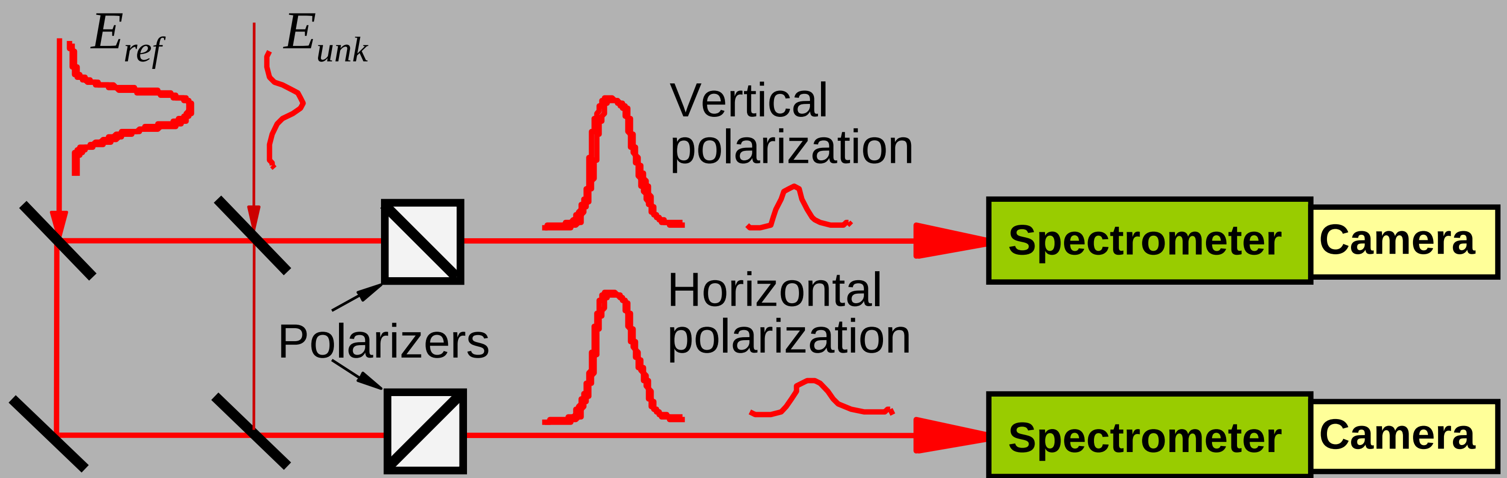


Pulse generated and measured by Matthew Coughlan and Robert Levis, Temple University

Unpolarized light doesn't exist…

...there is, however, light whose polarization state changes too rapidly to be measured with the available apparatus!

So measure $E(t)$ for both polarizations using two SI apparatuses:



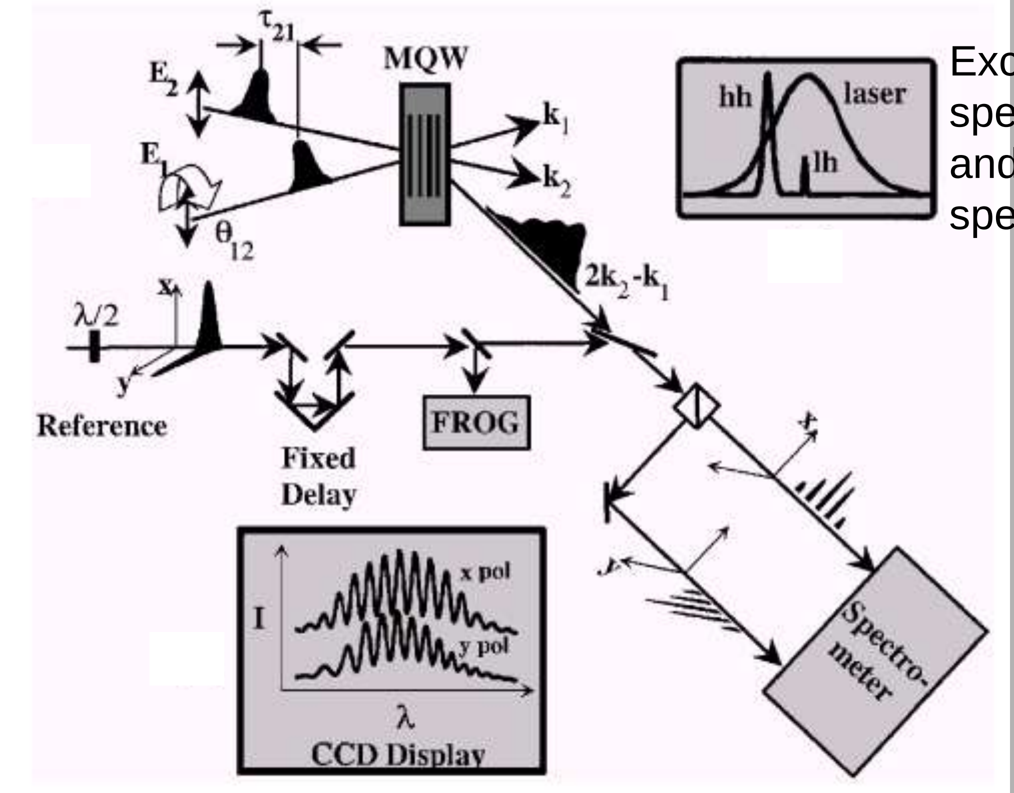
POLLIWOG (POLarization-Labeled Interference vs. Wavelength for Only a Glint*)

* Glint = "a very weak, very short pulse of light"

Walecki, Fittinghoff, Smirl, and Trebino, Opt. Lett. 22, 81 (1997)

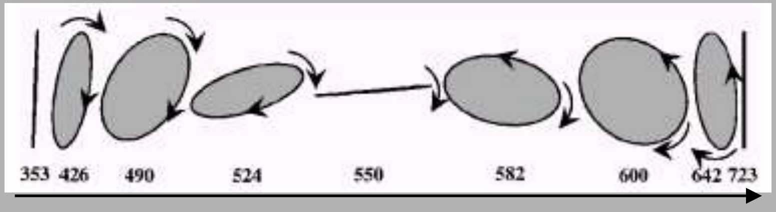
Application of POLLIWOG

Measurement of the variation of the polarization state of the emission from a GaAs-AlGaAs multiple quantum well when heavy-hole and light-hole excitons are excited elucidates the physics of these devices.



Excitation-laser spectrum and hh and lh exciton spectra

Evolution of the polarization of the emission:



A. L. Smirl, *et al., Optics Letters*, Vol. 23, No. 14 (1998)

Spectral Interferometry: Pros and Cons

Advantages

It's simple—requires only a beam-splitter and a spectrometer

It's linear and hence extremely sensitive. Only a few thousand photons are required.

Disadvantages

It measures only the spectral-phase difference.

A separately characterized reference pulse is required to measure the phase of a pulse.

The reference pulse must be the same color as the unknown pulse.

It requires careful alignment and good stability—it's an interferometer (but SEA TADPOLE fixes this).

Using spectral interferometry to measure a pulse *without a reference pulse*: SPIDER

If we perform spectral interferometry between a pulse and itself, the spectral phase cancels out. Perfect sinusoidal fringes always occur:

$$S_{SI}(\omega) = S_{unk}(\omega) + S_{unk}(\omega) + 2\sqrt{S_{unk}(\omega)}\sqrt{S_{unk}(\omega)}\cos[\varphi_{unk}(\omega) - \varphi_{unk}(\omega) + \omega T]$$

What if we frequency shift one pulse replica compared to the other:

$$S_{SI}(\omega) = S(\omega) + S(\omega+\delta\omega) + 2\sqrt{S(\omega)}\sqrt{S(\omega+\delta\omega)}\cos[\varphi(\omega+\delta\omega) - \varphi(\omega) + \omega T]$$

frequency shear

group delay

$$\phi_{SPIDER} = \varphi(\omega+\delta\omega) - \varphi(\omega) + \omega T = \delta\omega \frac{d\varphi}{d\omega} + \omega T$$

pulse separation

This measures the derivative of the spectral phase (the group delay).

This technique is called: Spectral Phase Interferometry for Direct Electric-Field Reconstruction (SPIDER).

Iaconis and Walmsley, JQE 35, 501 (1999).

Advantages and Disadvantages of SPIDER

Advantages

Pulse retrieval is direct (i.e., non-iterative) and hence fast.
Minimal data are required: only one spectrum yields the spectral phase.
It naturally operates single-shot.

Disadvantages

Its apparatus is **very** complicated. It has 12 sensitive alignment parameters
(5 for the Michelson; 4 in pulse stretching; 1 for pulse timing;
2 for spatial overlap in the SHG crystal; not counting the spectrometer).
Like SI, it requires very high mechanical stability, or the fringes wash out.
Poor beam quality can also wash out the fringes, preventing the measurement.
It has no independent checks or feedback, and no marginals are available.
It cannot measure long or complex pulses: TBP < ~ 3. (Spectral resolution is
~10 times worse than that of the spectrometer due to the need for fringes.)
It has poor sensitivity due to the need to split and stretch the pulse
before the nonlinear medium.
The pulse delay must be chosen for the particular pulse. And pulse structure
can confuse it, yielding ambiguities.

How could so many researchers have made meaningless measurements?

Over 100 publications have occurred using SPIDER—all with meaningless results. Why didn't anyone notice this earlier?

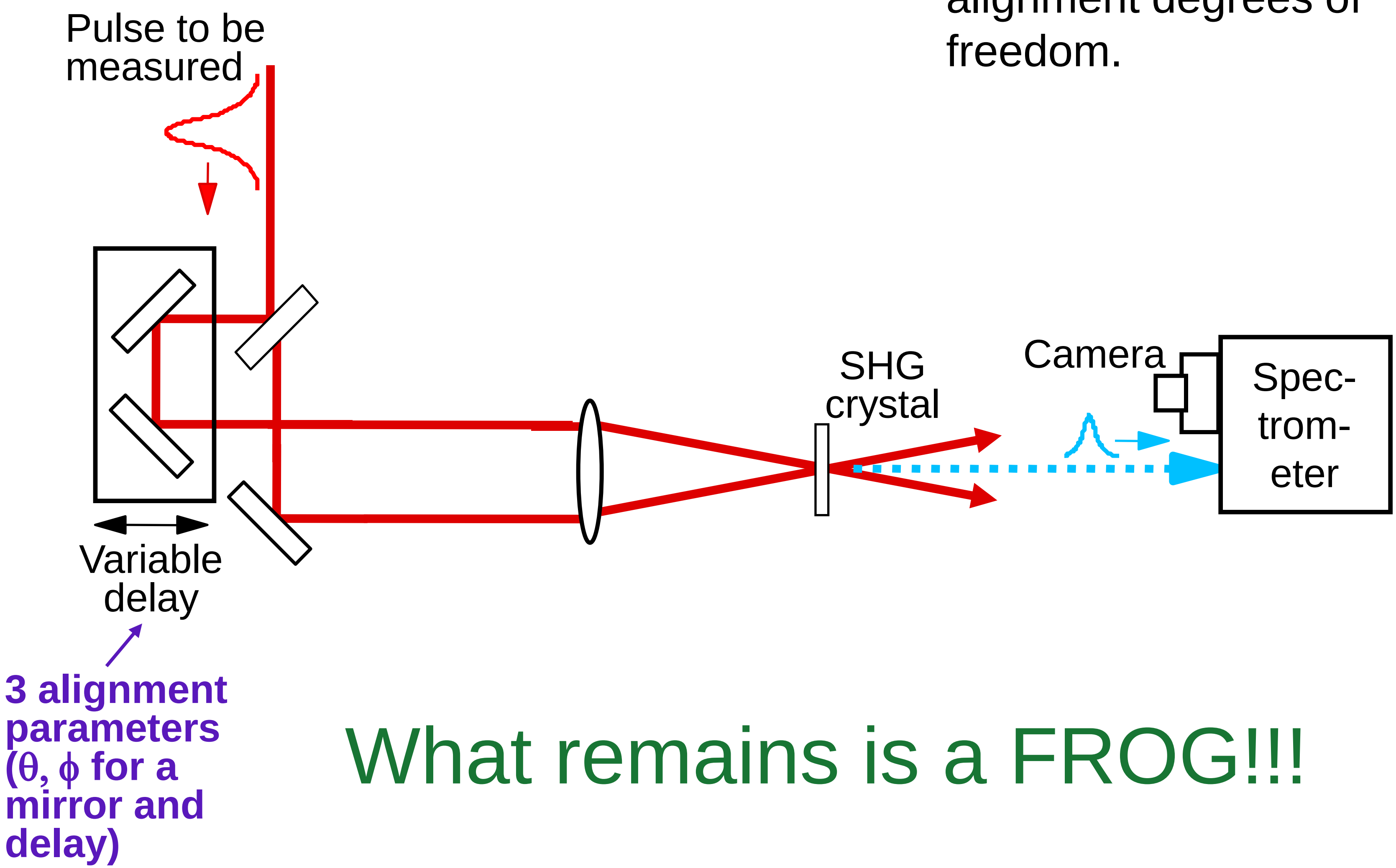
Many researchers wanted desperately to obtain the shortest pulse.

So they used a method (SPIDER) that allowed them to align the measurement device (not the laser!) to give the shortest pulse.

This is very bad science.

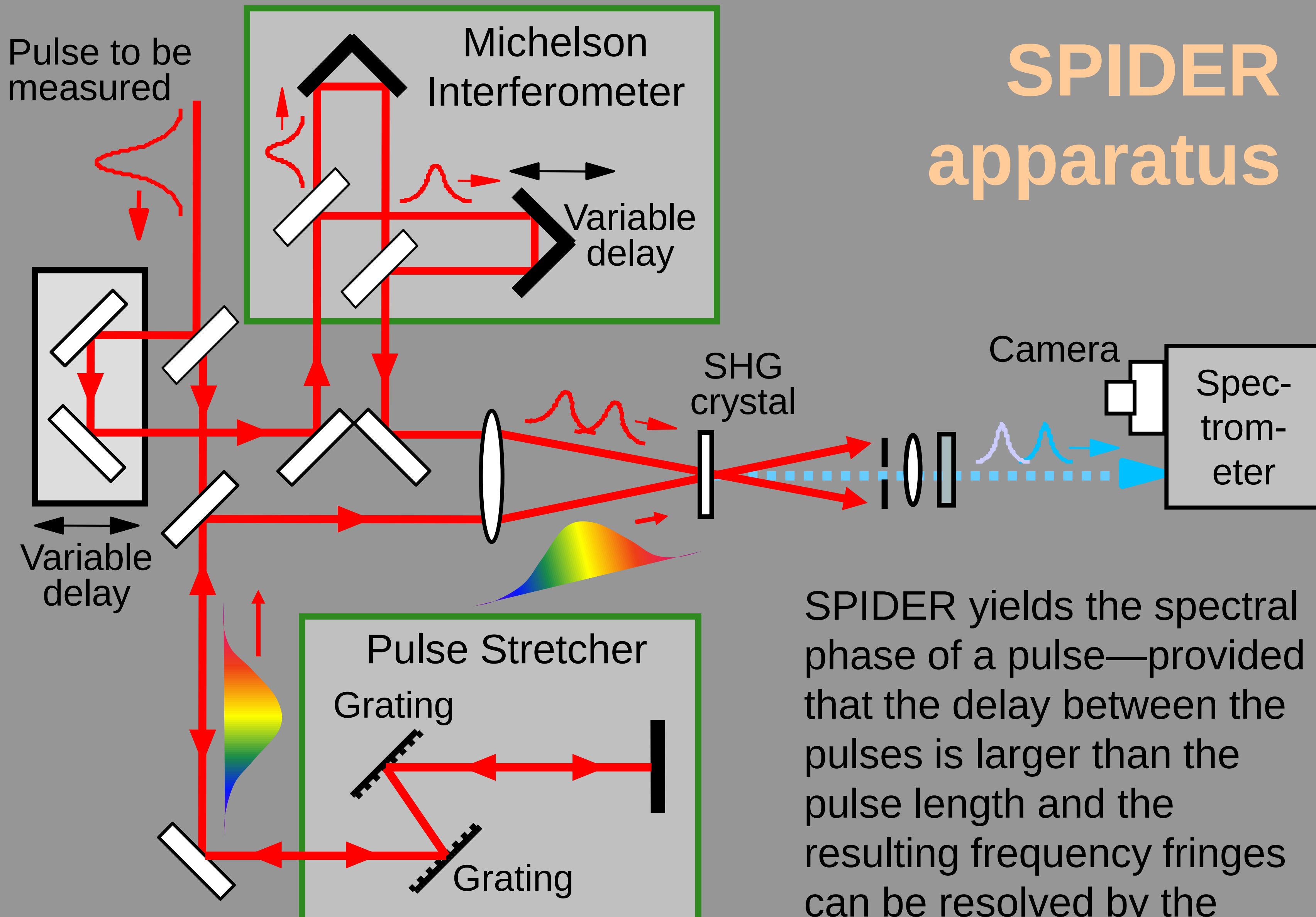
Can we simplify SPIDER?

SPIDER has 12 sensitive alignment degrees of freedom.



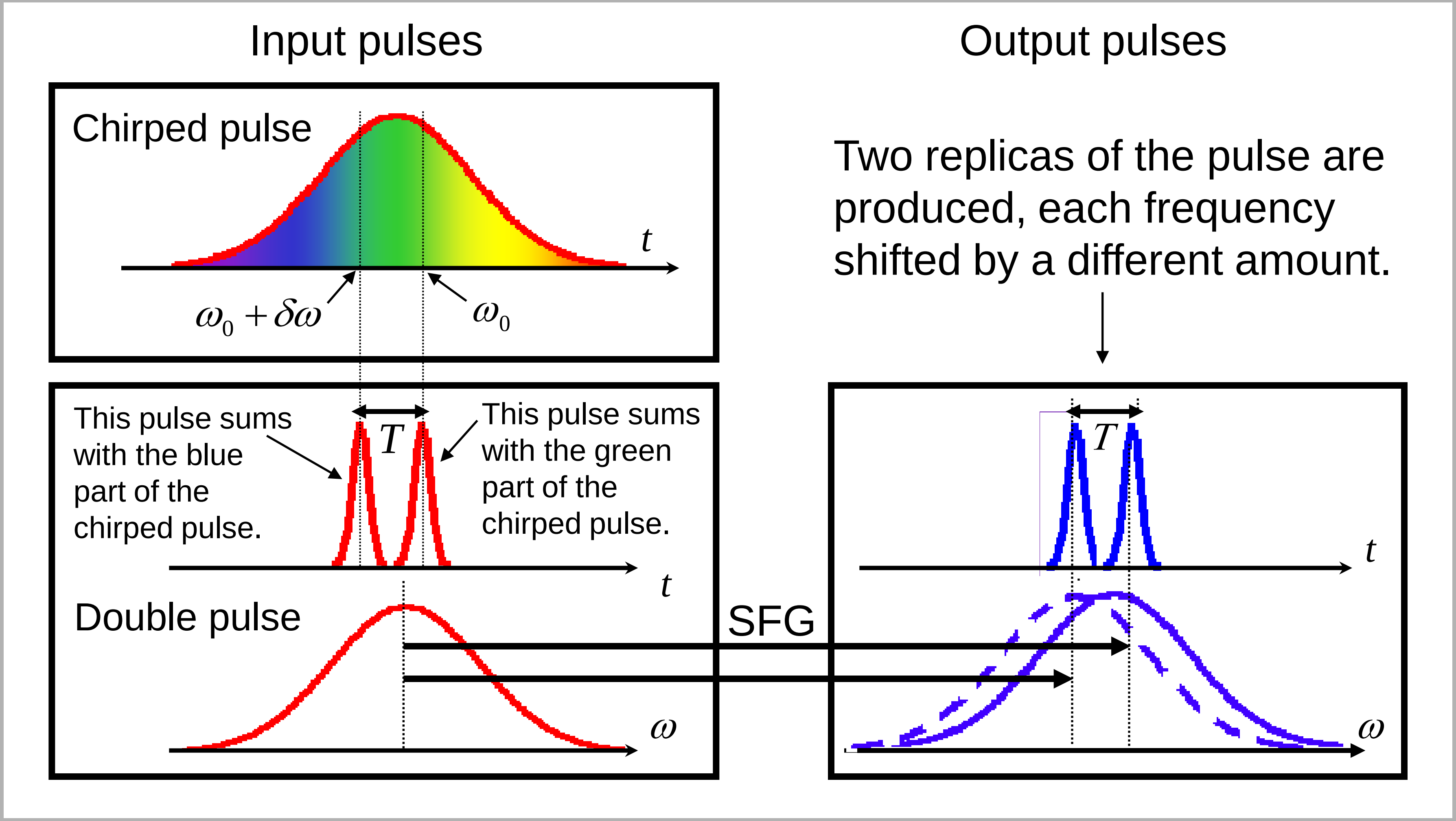
What remains is a FROG!!!

SPIDER apparatus



SPIDER yields the spectral phase of a pulse—provided that the delay between the pulses is larger than the pulse length and the resulting frequency fringes can be resolved by the spectrometer.

How SPIDER works



Performing SI on these two pulses yields the difference in spectral phase at nearby frequencies (separated by $\delta\omega$). This yields the spectral phase.

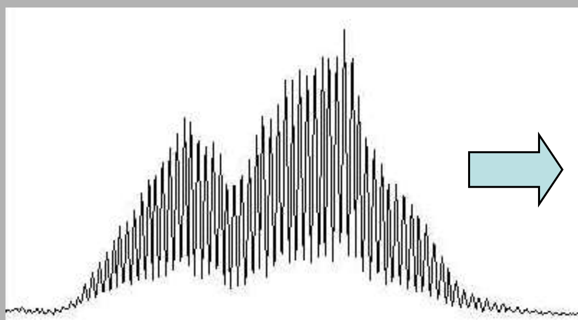
C. Iaconis, I. A. Walmsley, *Spectral phase interferometry for direct electric-field reconstruction of ultrashort optical pulses*, Opt. Lett. **23**, 792 (1998)

SPIDER: extraction of the spectral phase

Extraction of the spectral phase

L. Gallmann et al, Opt. Lett., **24**, 1314 (1999)

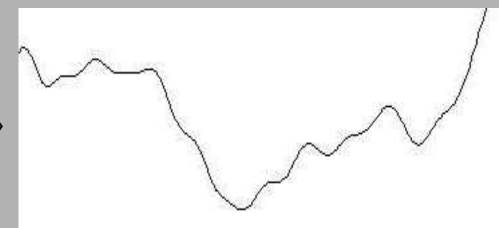
Measurement of the interferogram



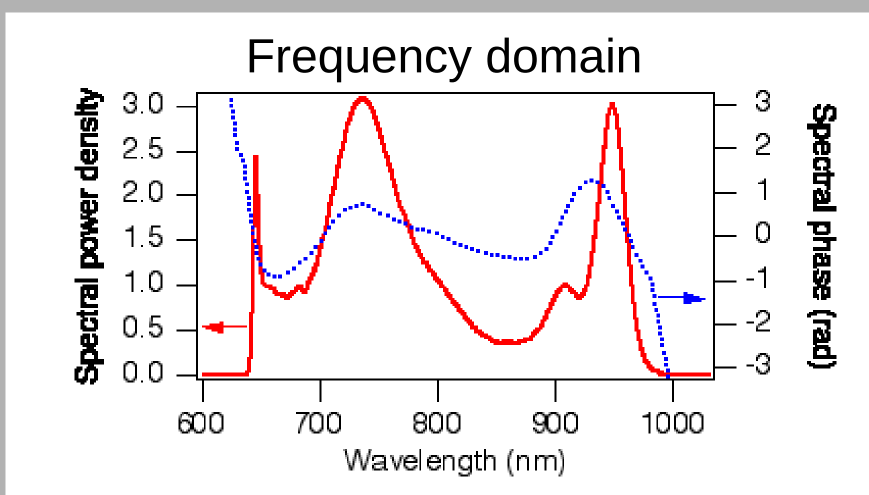
Extraction of their spectral phase difference using spectral interferometry

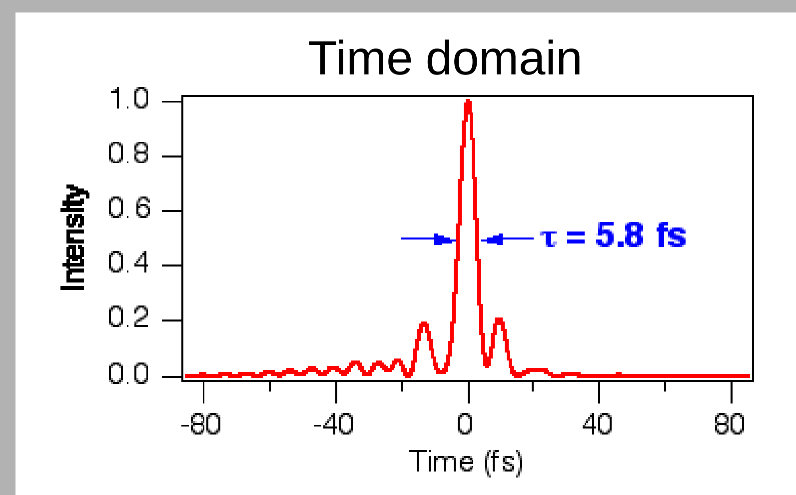
$$\varphi(\omega+\delta\omega)-\varphi(\omega)$$

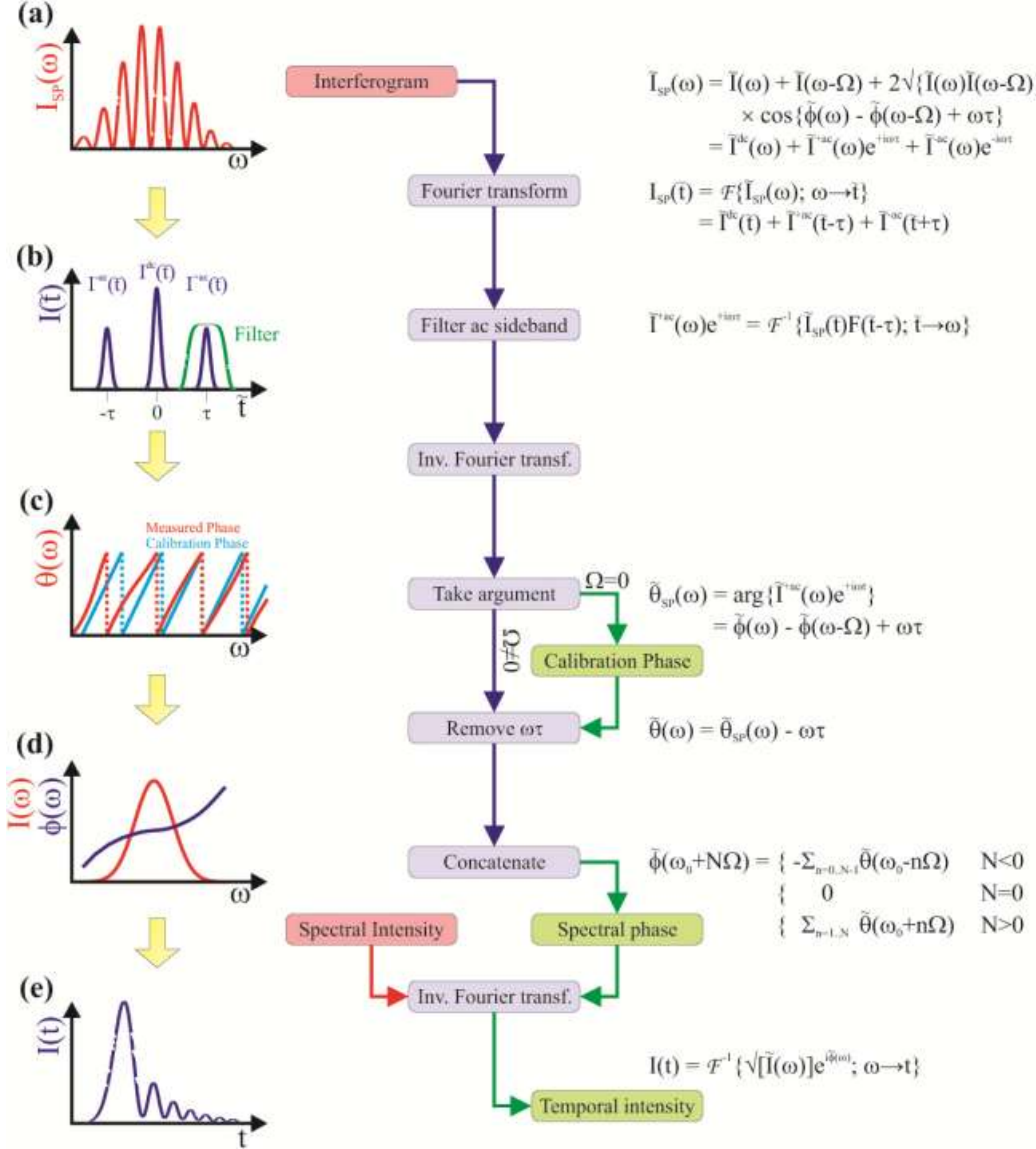
Integration of the phase



$$\varphi(\omega)$$

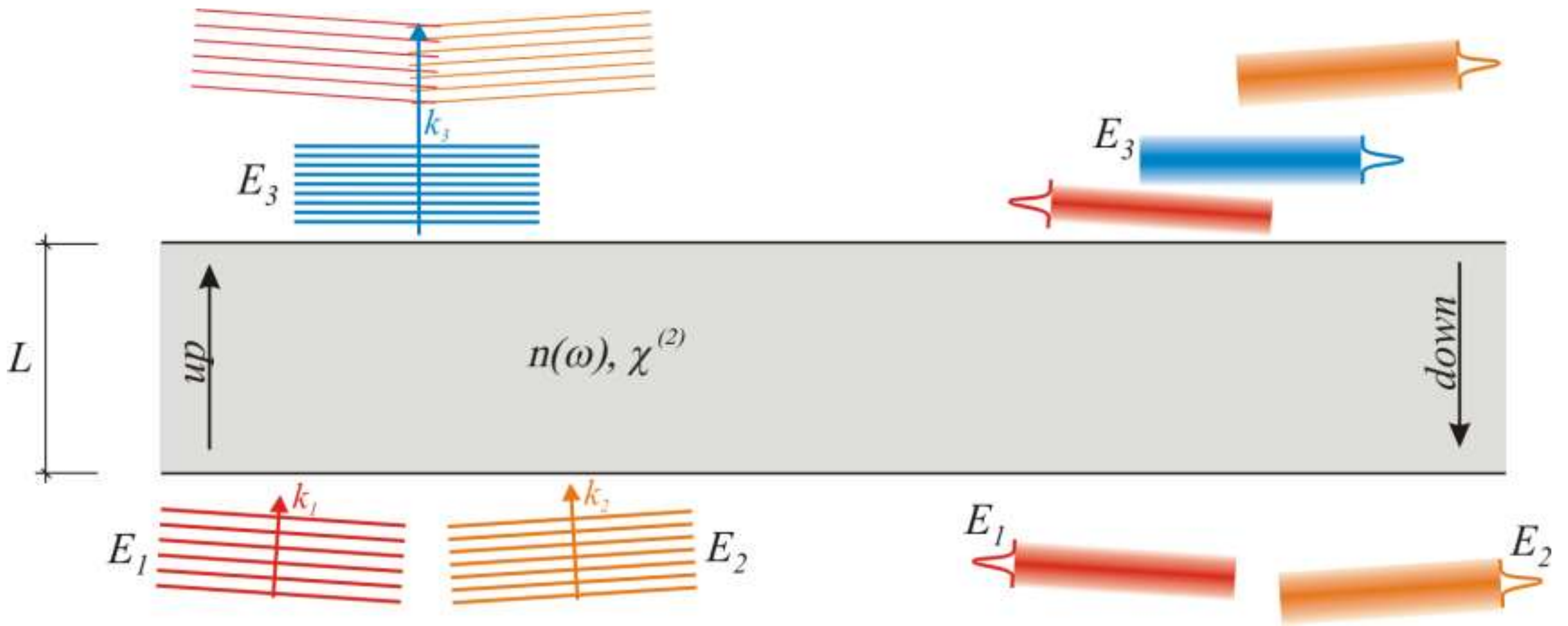




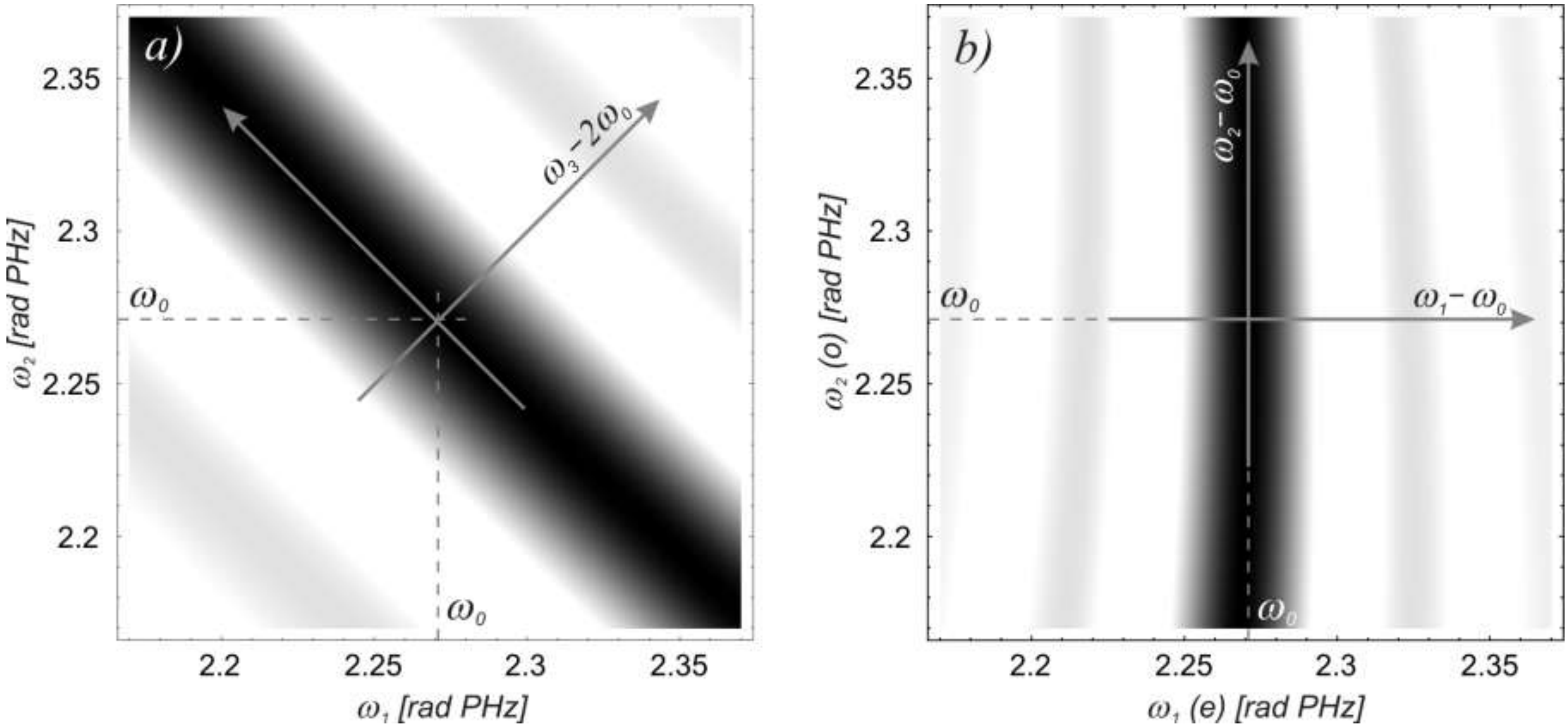


(a)
(b)
(c)
(d)
(e)
Filter
Measured Phase
Calibration Phase
Interferogram
Fourier transform
Filter ac sideband
Inv. Fourier transf.
Take argument
Ω=0
Ω≠0
Calibration Phase
Remove ωτ
Concatenate
Spectral Intensity
Spectral phase
Inv. Fourier transf.
Temporal intensity

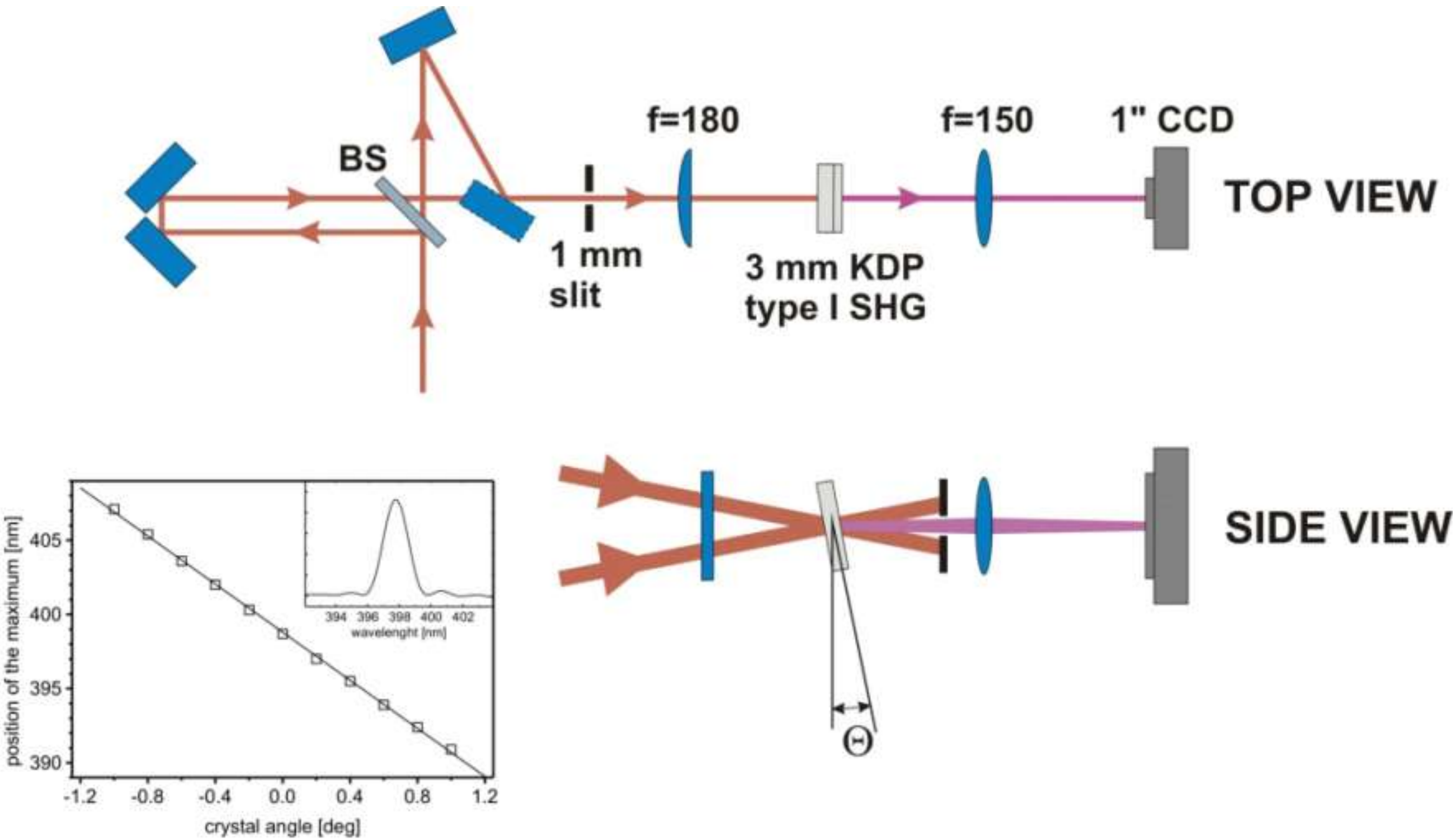
Wave mixing for CW and pulsed fields



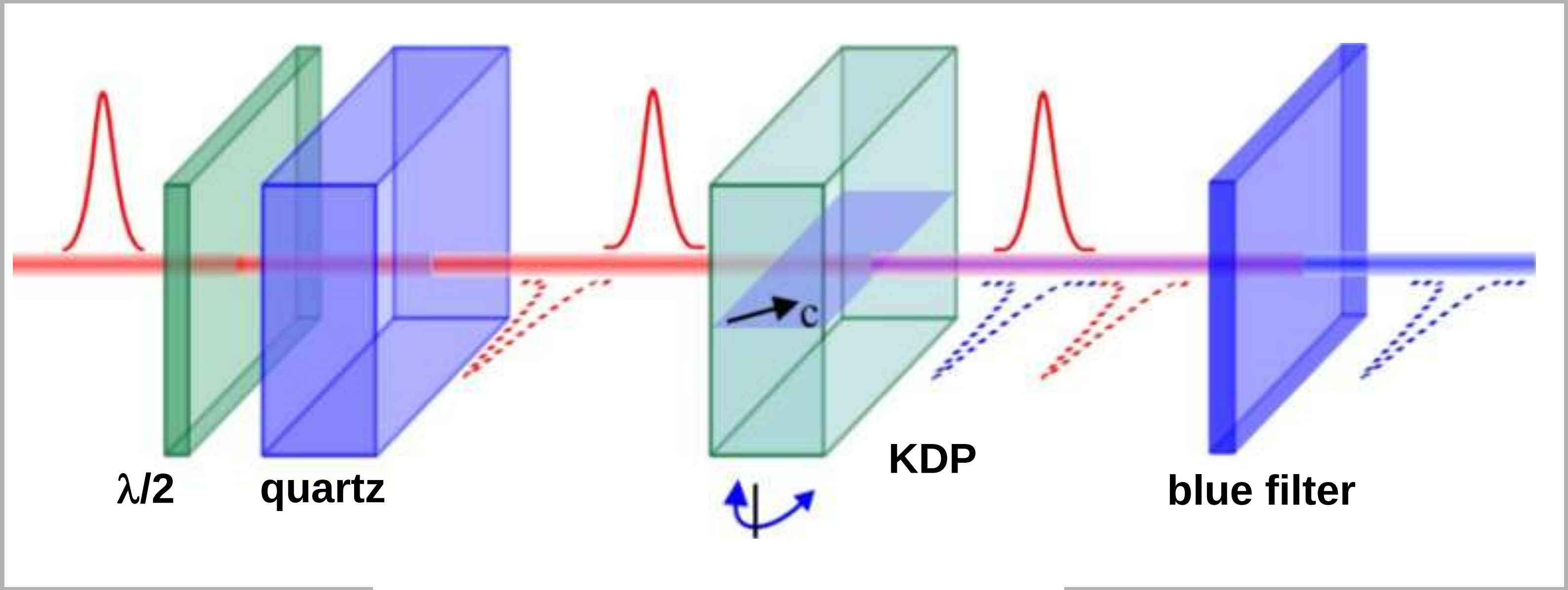
type I and type II SFG in a KDP crystal

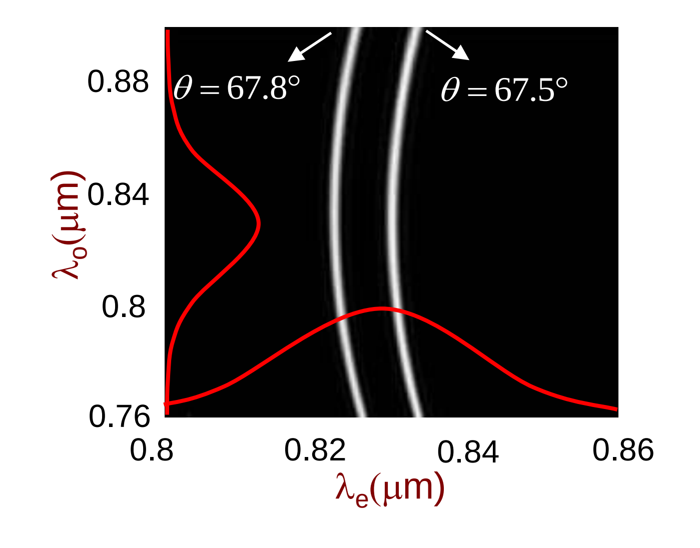


Poor Man's FROG – the first prototype

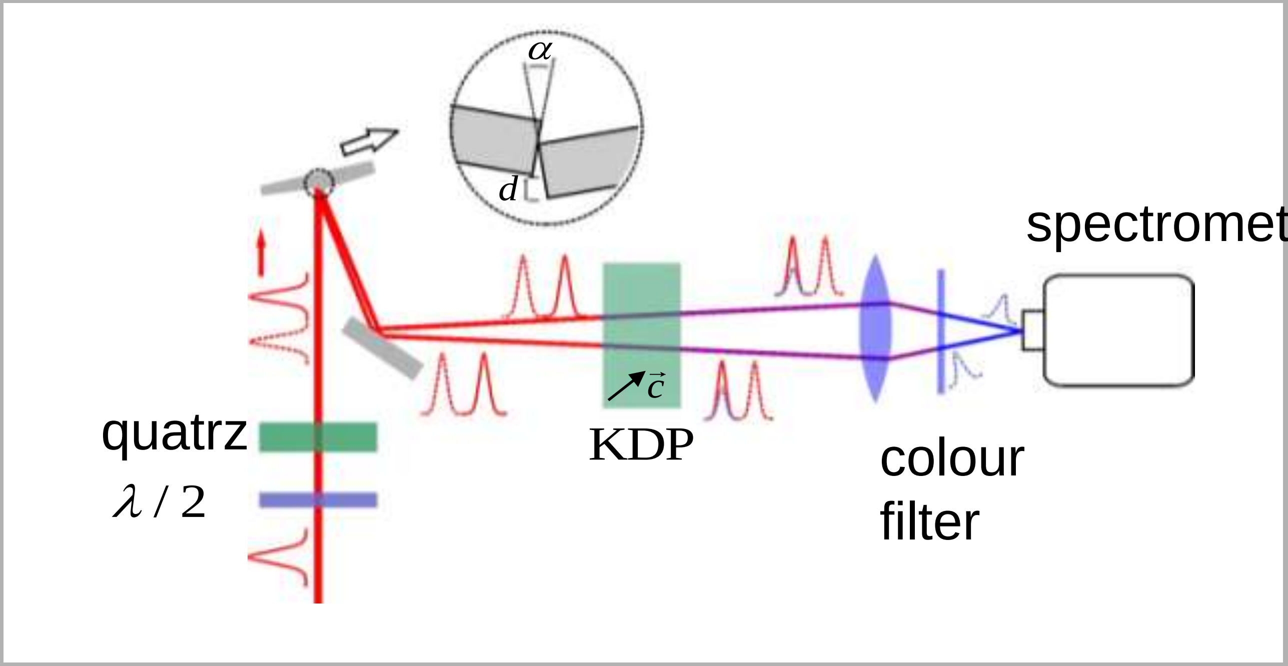


Sum Frequency Generation in a type II thick crystal





Early layout – ARAIGNEE



quartz : 10mm

$\Rightarrow \quad t_0 = 317$ fs

$\alpha \approx 0.5°$

$\Rightarrow \quad \Omega \approx 0.5$ nm

$d \approx 0.45$ mm

$\Rightarrow \quad \tau \approx 1.5$ ps

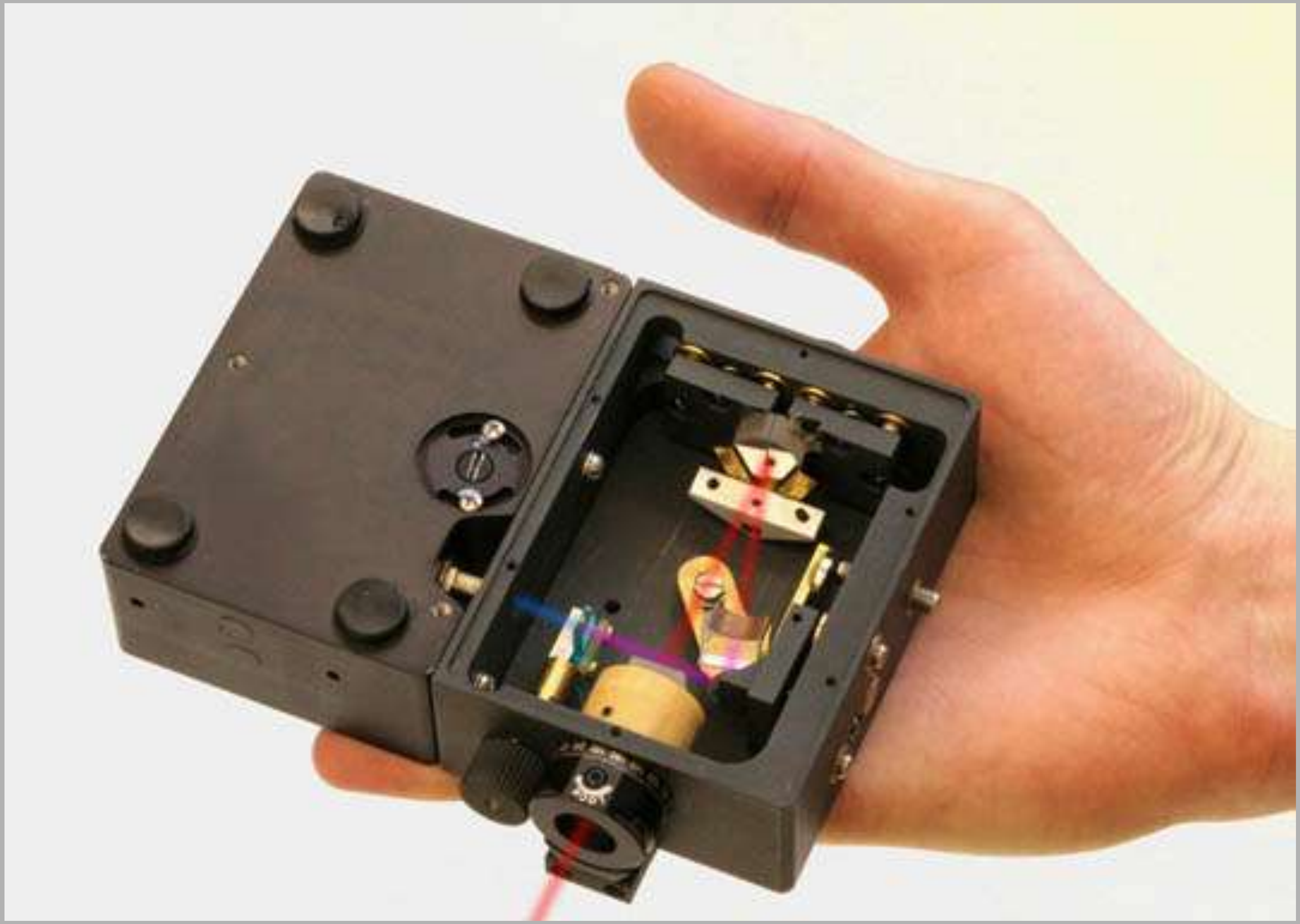
KDP : 5mm

$\Rightarrow \quad \Delta t_{max} = 360$ fs

- simple setup - 9 x 12 cm
- precise determination of the shear Ω
- ‘automatic’ spatial and temporal overlap in the SFG crystal
- beam diameter : 2-5 mm

A. Radunsky, E. Kosik Williamsy, I. Walmsley, P. Wasylczyk, W. Wasilewski, A. U'Ren, M. Anderson, *Simplified Spectral Phase Interferometry for Direct Electric-Field Reconstruction using a thick nonlinear crystal*, Opt. Lett. **31**, 1008 (2006)

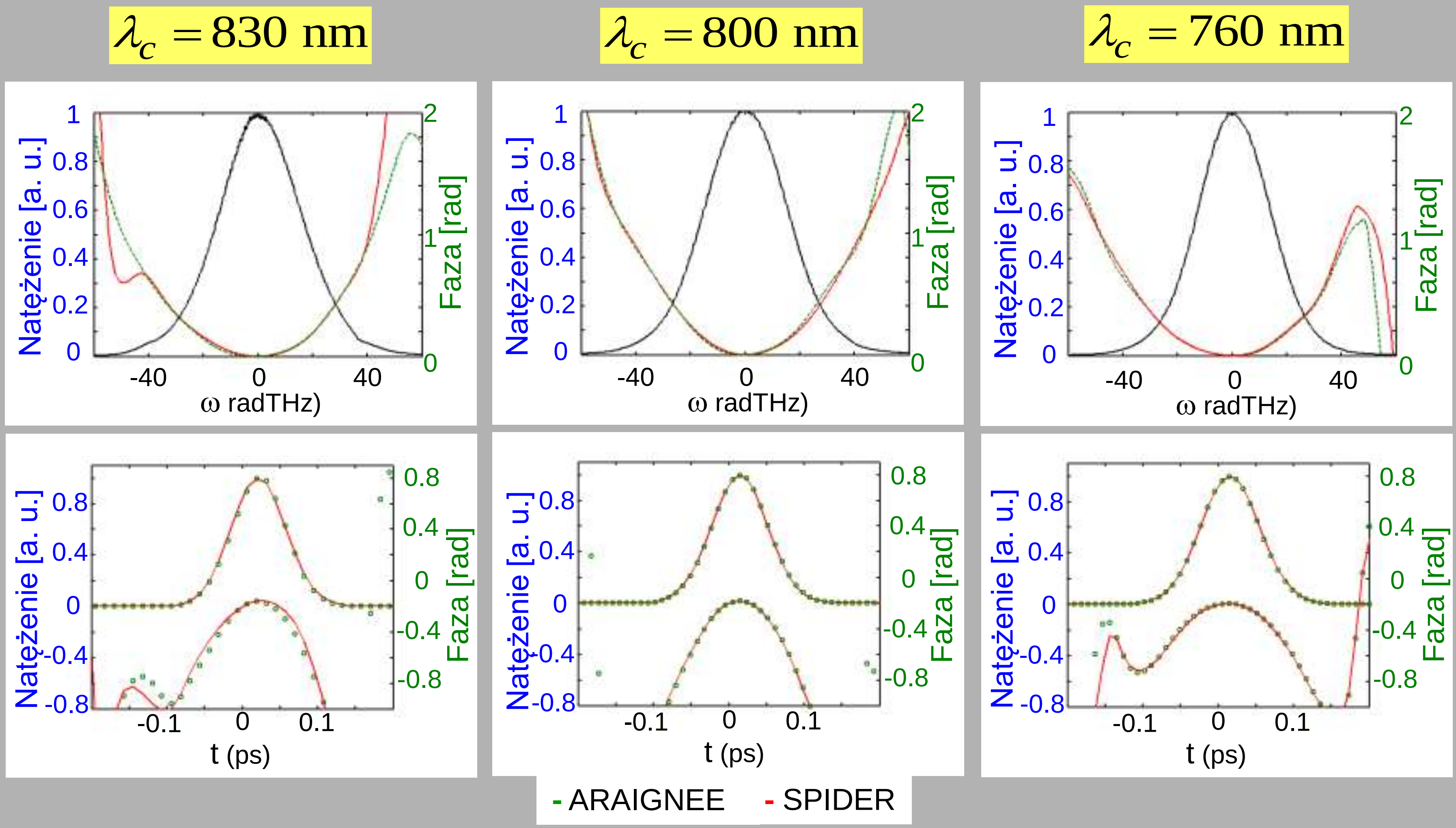
μSPIDER comes in handy, from Oxford…



A. S. Radunsky, I. A. Walmsley, S.-P. Gorza, P. Wasylczyk, *Compact spectral shearing interferometer for ultrashort pulse characterization*, Opt. Lett. **32**, 181 (2007)

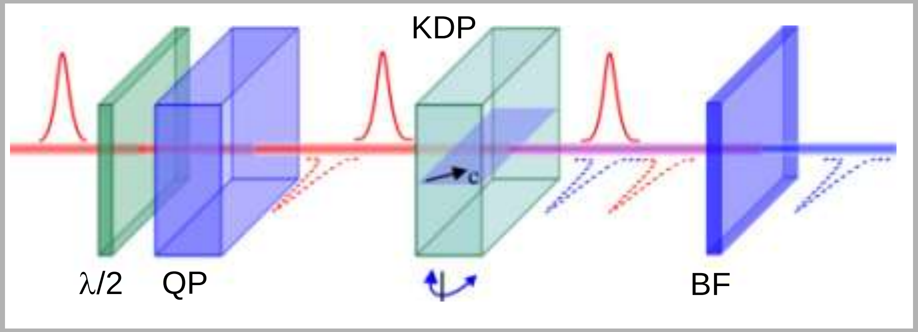
… and from Berlin (by APE)

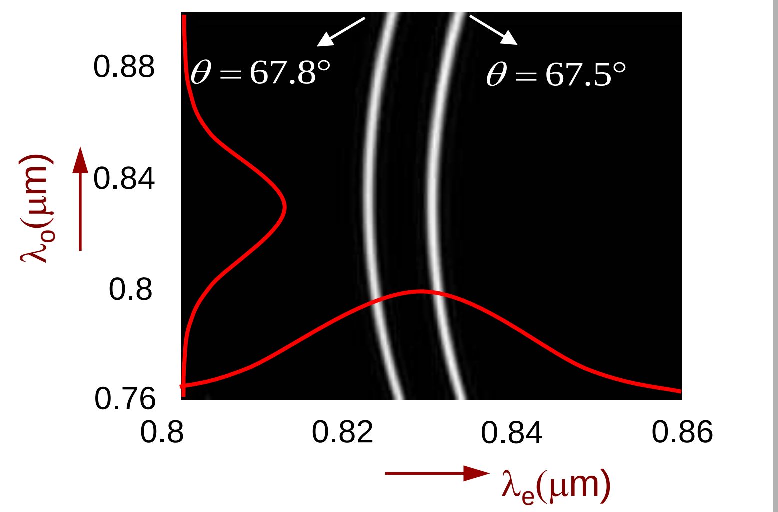
Other wavelengths



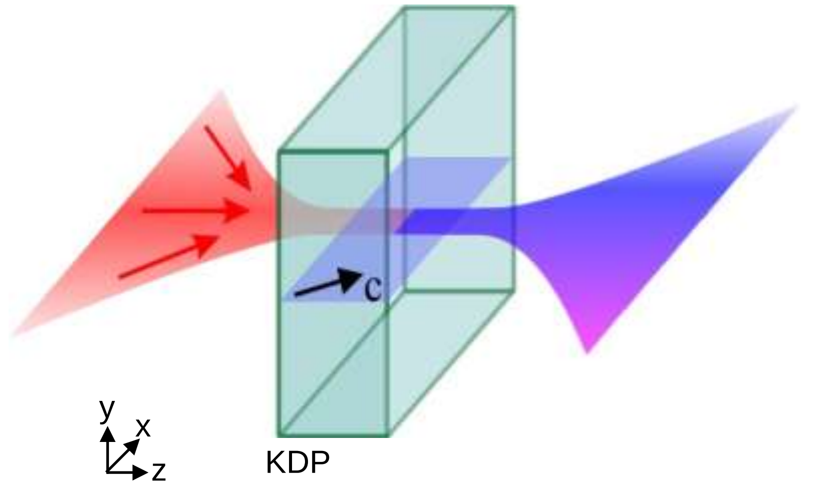
S.-P. Gorza, A. S. Radunsky, P. Wasylczyk, I. A. Walmsley, *Tailoring the phase-matching function for ultrashort pulse characterization by spectral shearing interferometry*, JOSA B **24**, 2064 (2007)

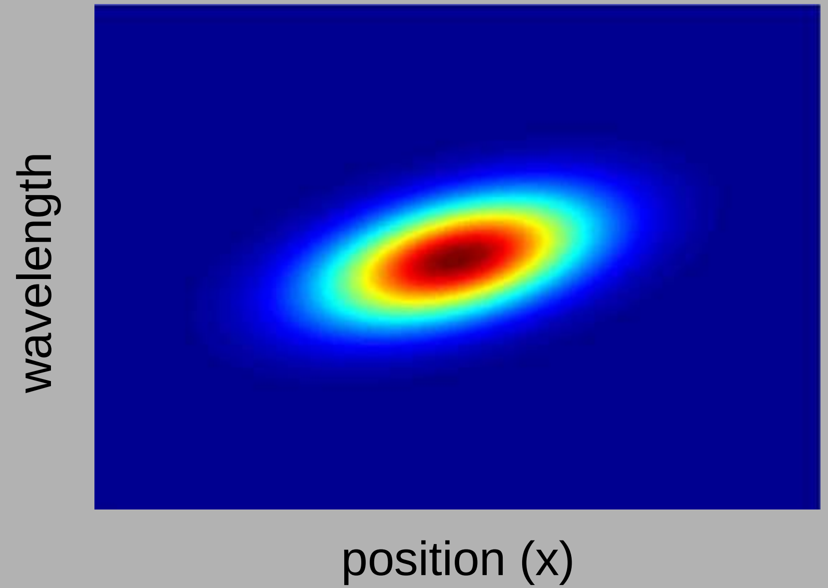
SFG in a thick crystal – now a bit modified



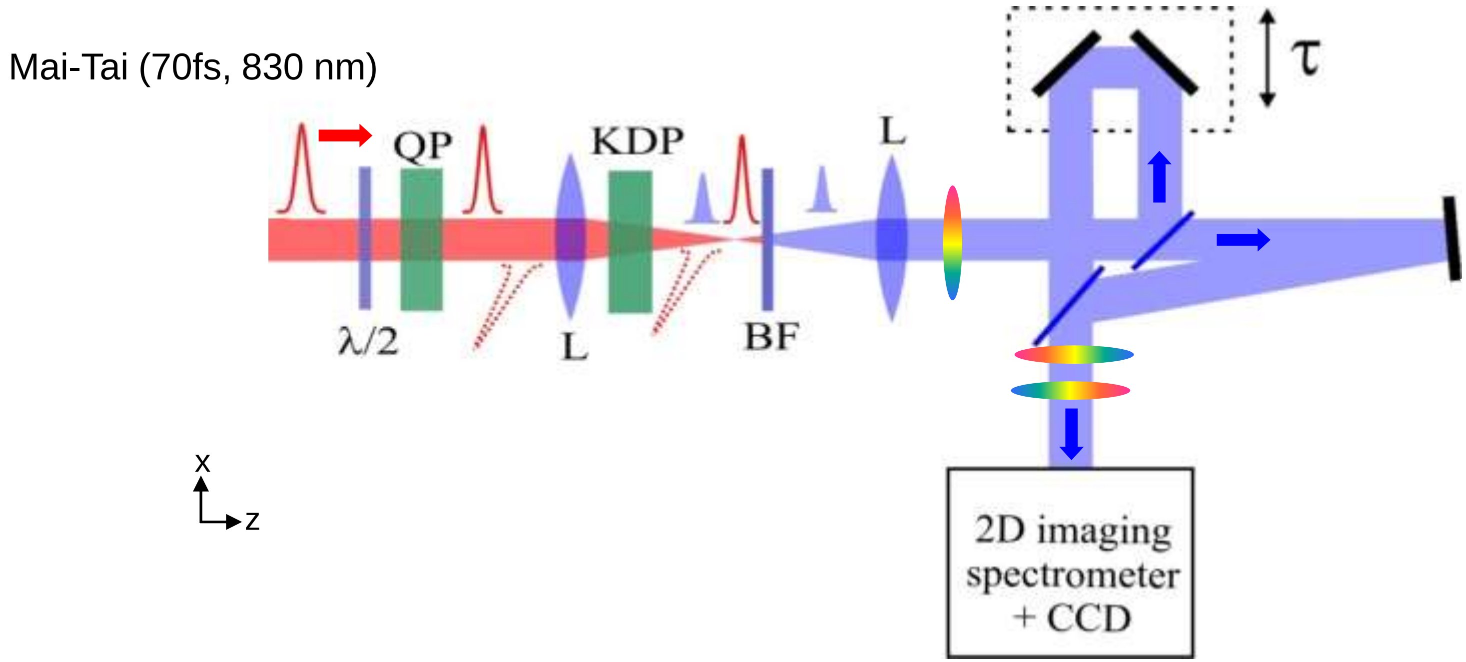


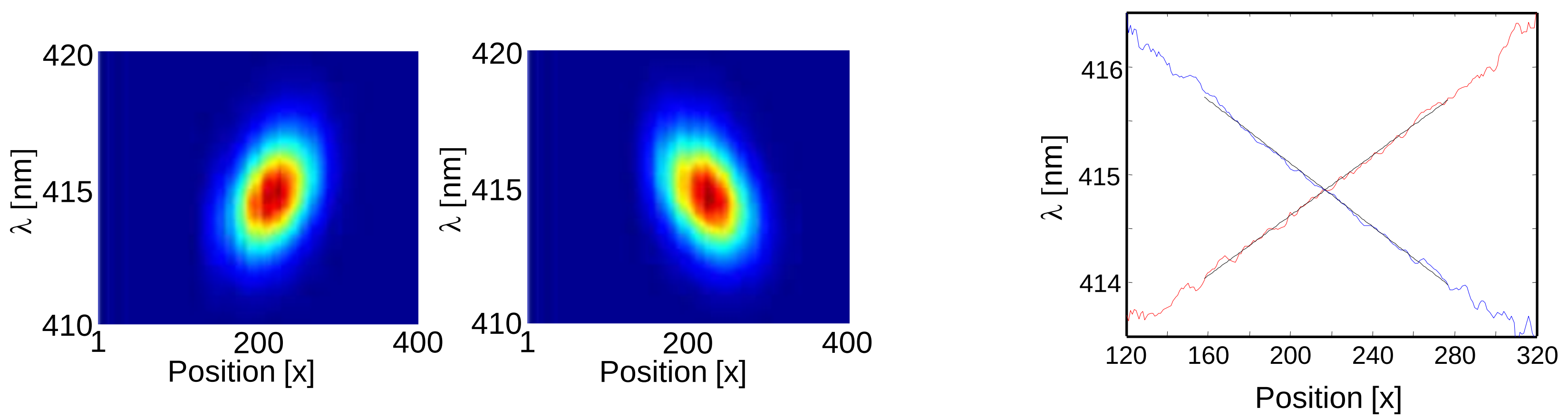
now, let us have a **focused** beam



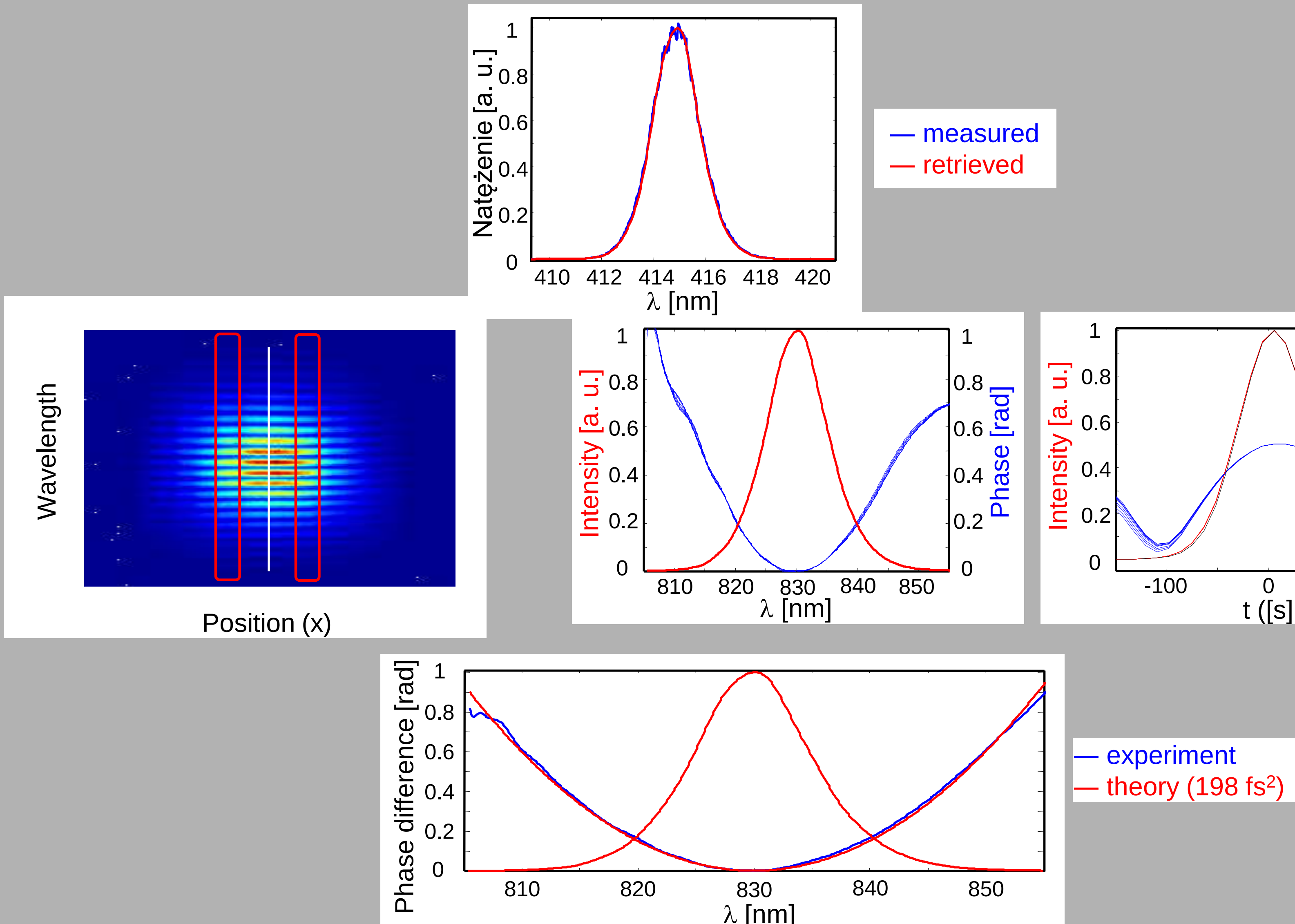


"Slanted" spectra





Can this measure something?



S.-P. Gorza, P. Wasylczyk, I. A. Walmsley, *Spectral shearing interferometry with spatially chirped replicas for measuring ultrashort pulses*, Opt. Expr. **23,** 15168 (2007)

More on SPIDER accuracy
at the end of the lecture notes

Spatio-temporal intensity-and-phase measurement

Why?

Spatial distortions in stretchers/compressors.

Pulse front distortions due to lenses.

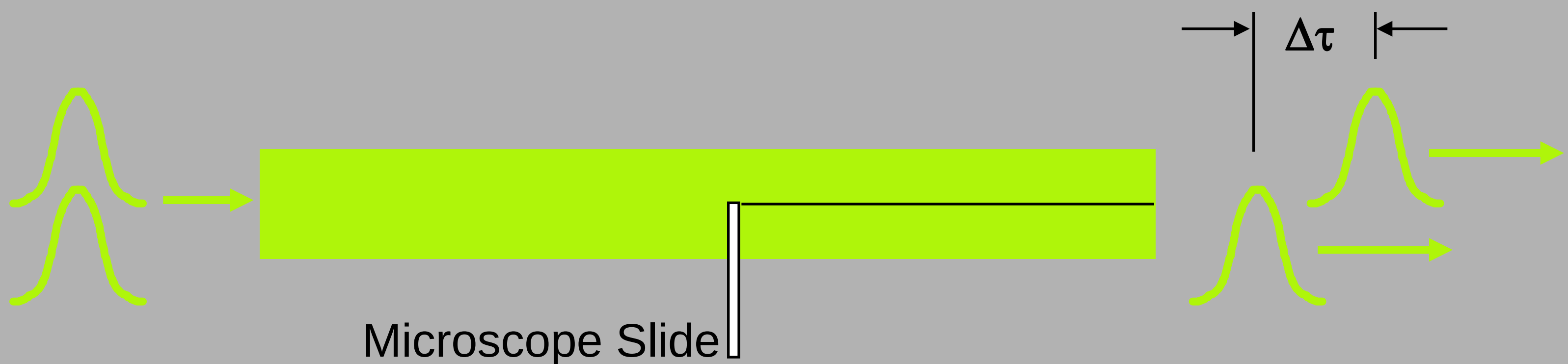
Structure of inhomogeneous materials.

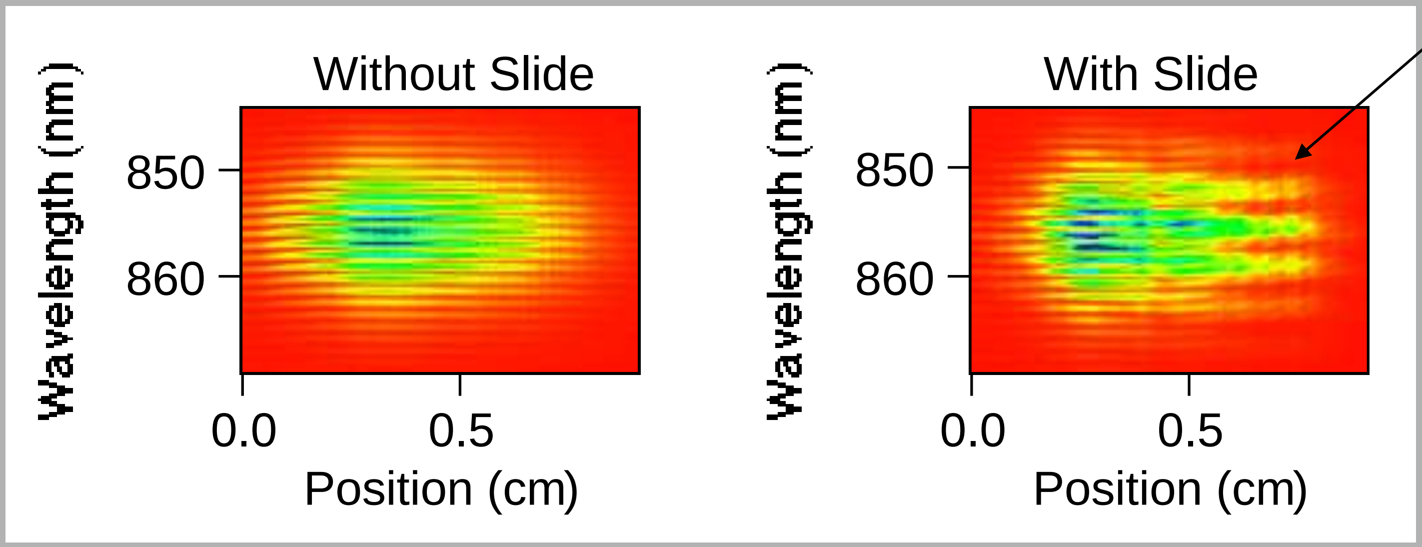
Pulse propagation in plasmas and other materials

Anything with a beam that changes in space as well as time!

Measuring the Intensity and Phase vs. Time *and Space*

Spectral interferometry only requires measuring one spectrum.
Using the other dimension of the CCD camera for position,
we can measure the pulse along one spatial dimension, also.

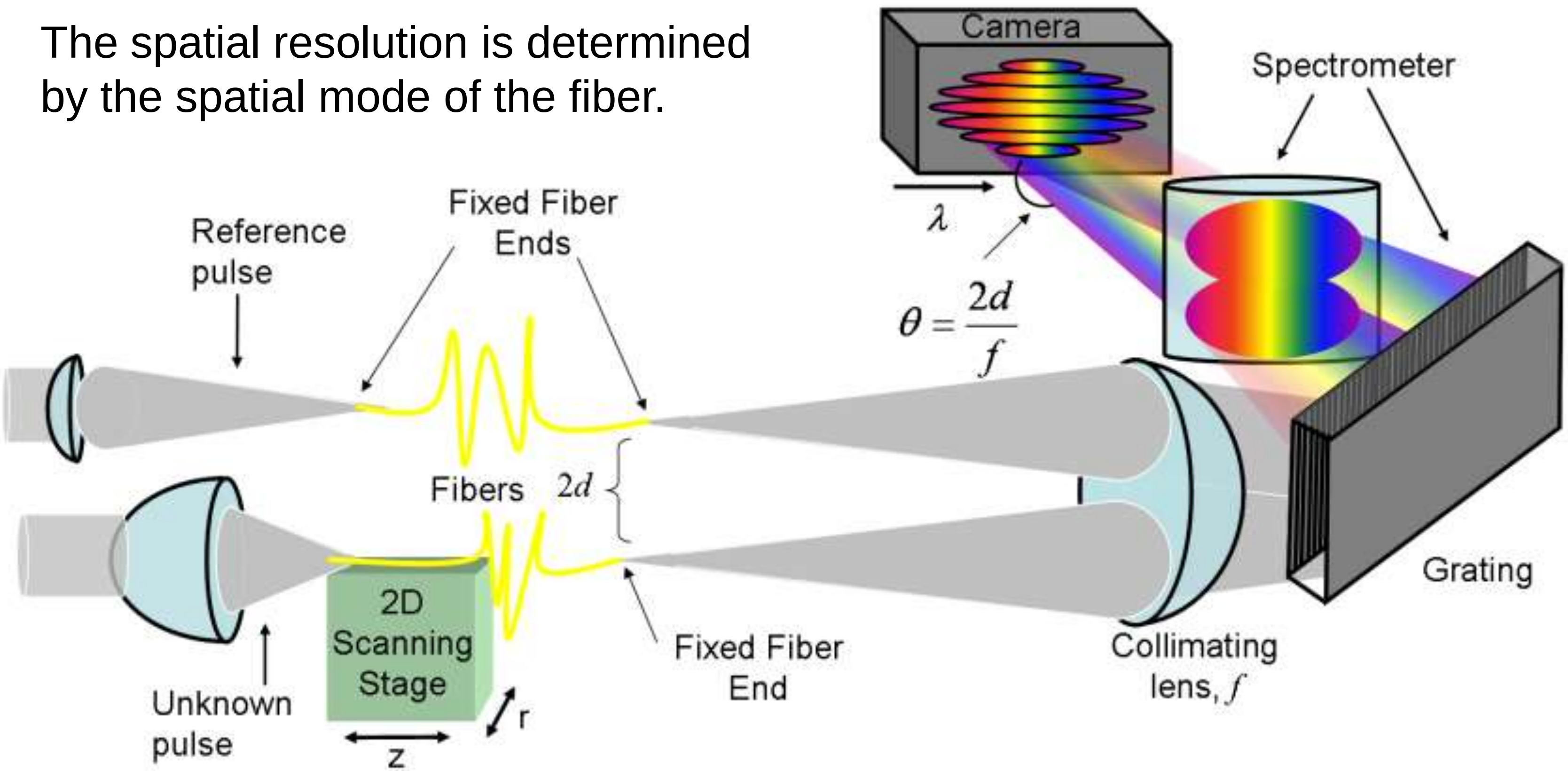




Fringe spacing is larger due to delay produced by slide (ref pulse was later).

Scanning SEA TADPOLE: E(x,y,z,t)

The spatial resolution is determined by the spatial mode of the fiber.

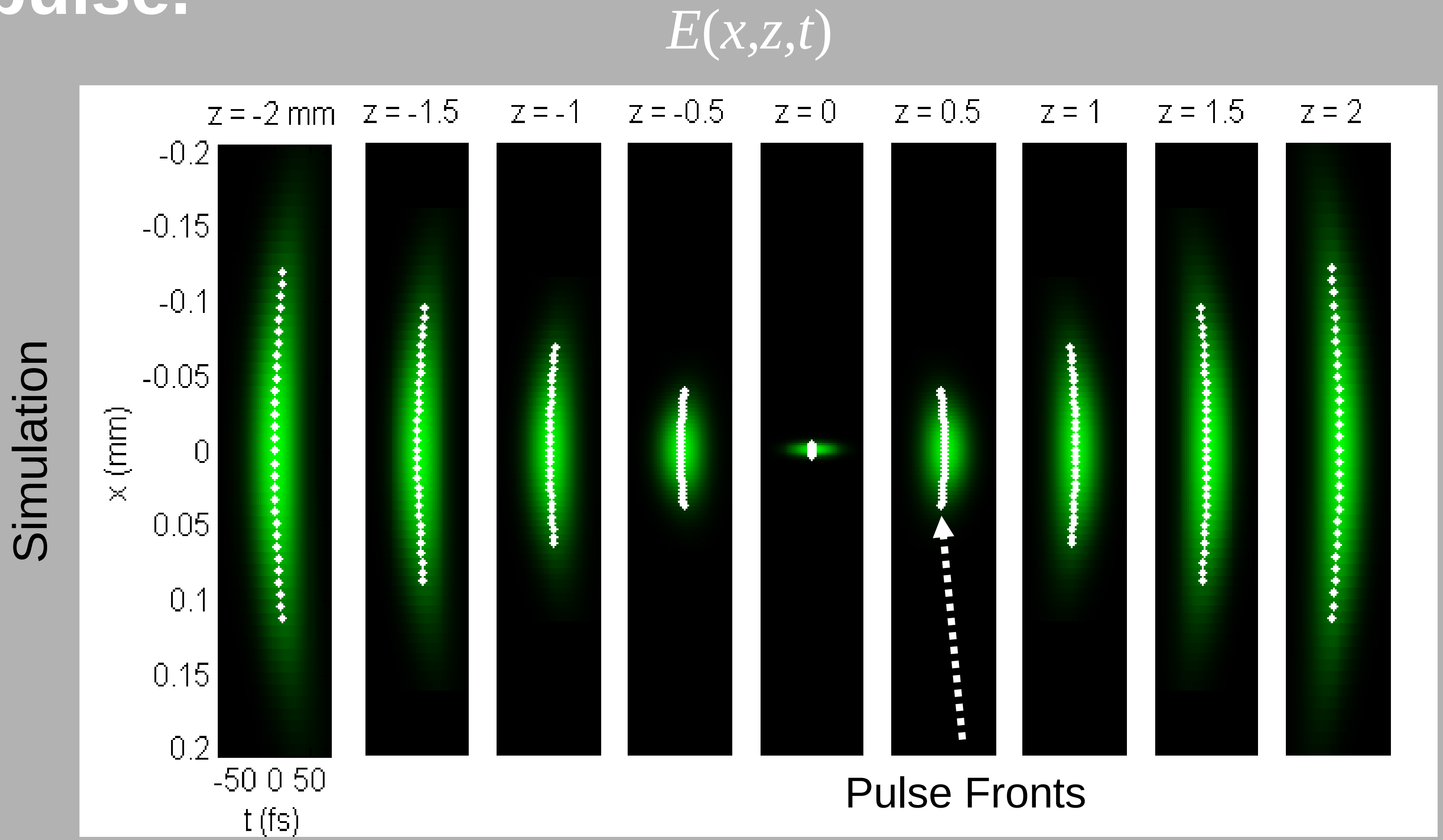


By scanning the input end of the unknown-pulse fiber, we can measure $\tilde{E}(\omega)$ at different positions yielding $\tilde{E}(x,y,z,\omega)$.

So we can measure even focusing pulses!

Pam Bowlan

E(x,z,t) for a theoretically perfectly focused pulse.



Color is the instantaneous frequency vs. x and t.

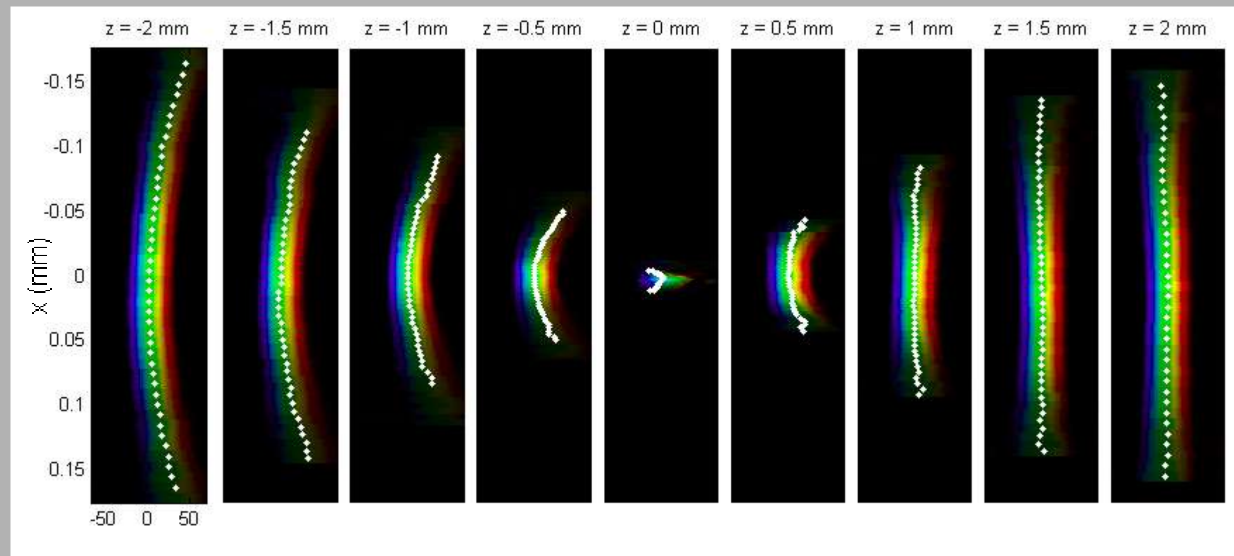
Uniform color indicates a lack of phase distortions.

Measuring E(x,z,t) for a focused pulse.

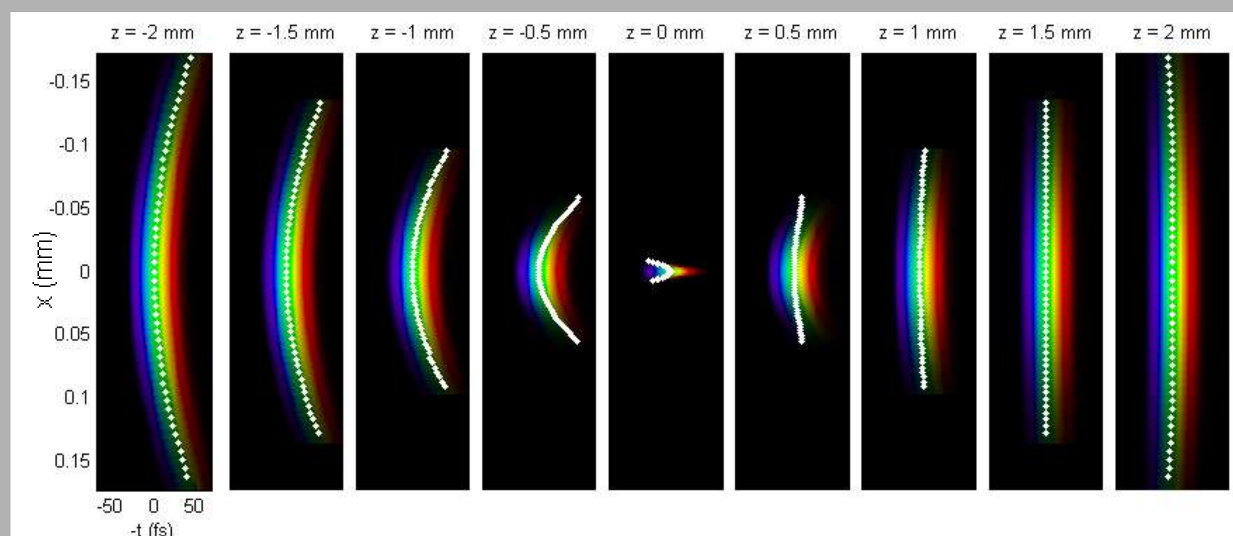
Aspheric PMMA lens with chromatic (but no spherical) aberration and GDD.

f = 50 mm
NA = 0.03

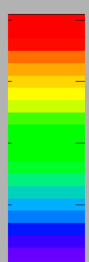
Measurement



Simulation



810 nm

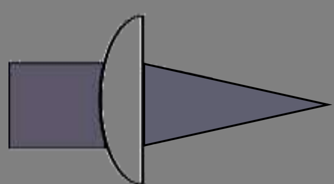


790 nm

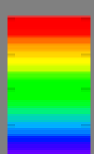
Spherical and chromatic aberration

Singlet BK-7 plano-convex lens with spherical and chromatic aberration and GDD.

f = 50 mm
NA = 0.03

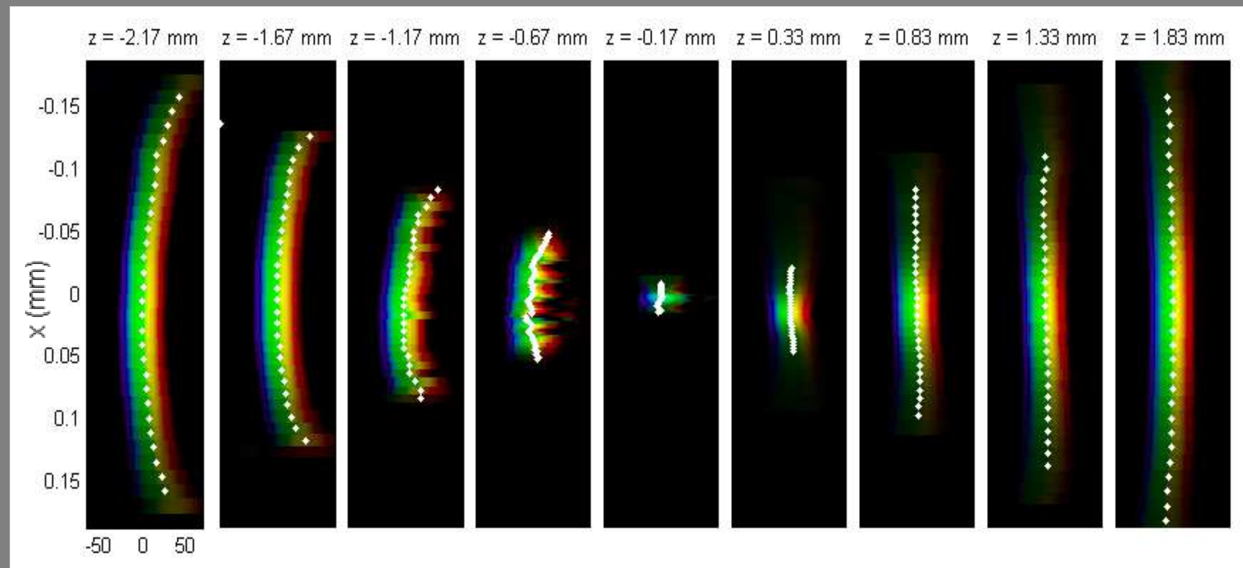


810 nm

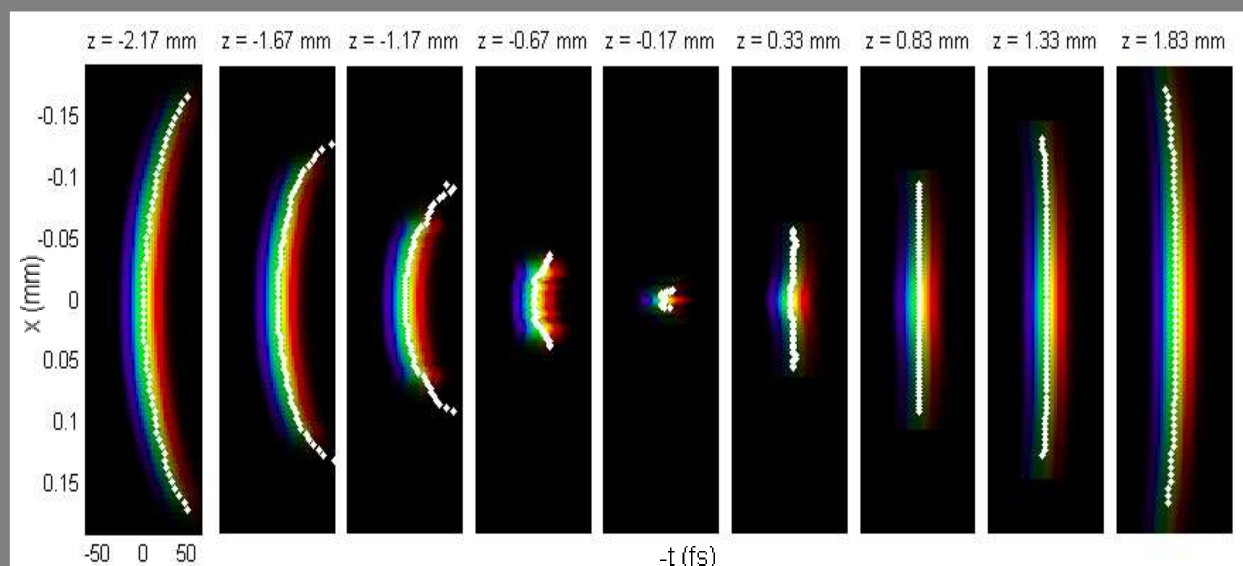


790 nm

Measurement



Simulation

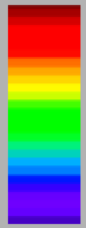


Distortions are more pronounced for a tighter focus.

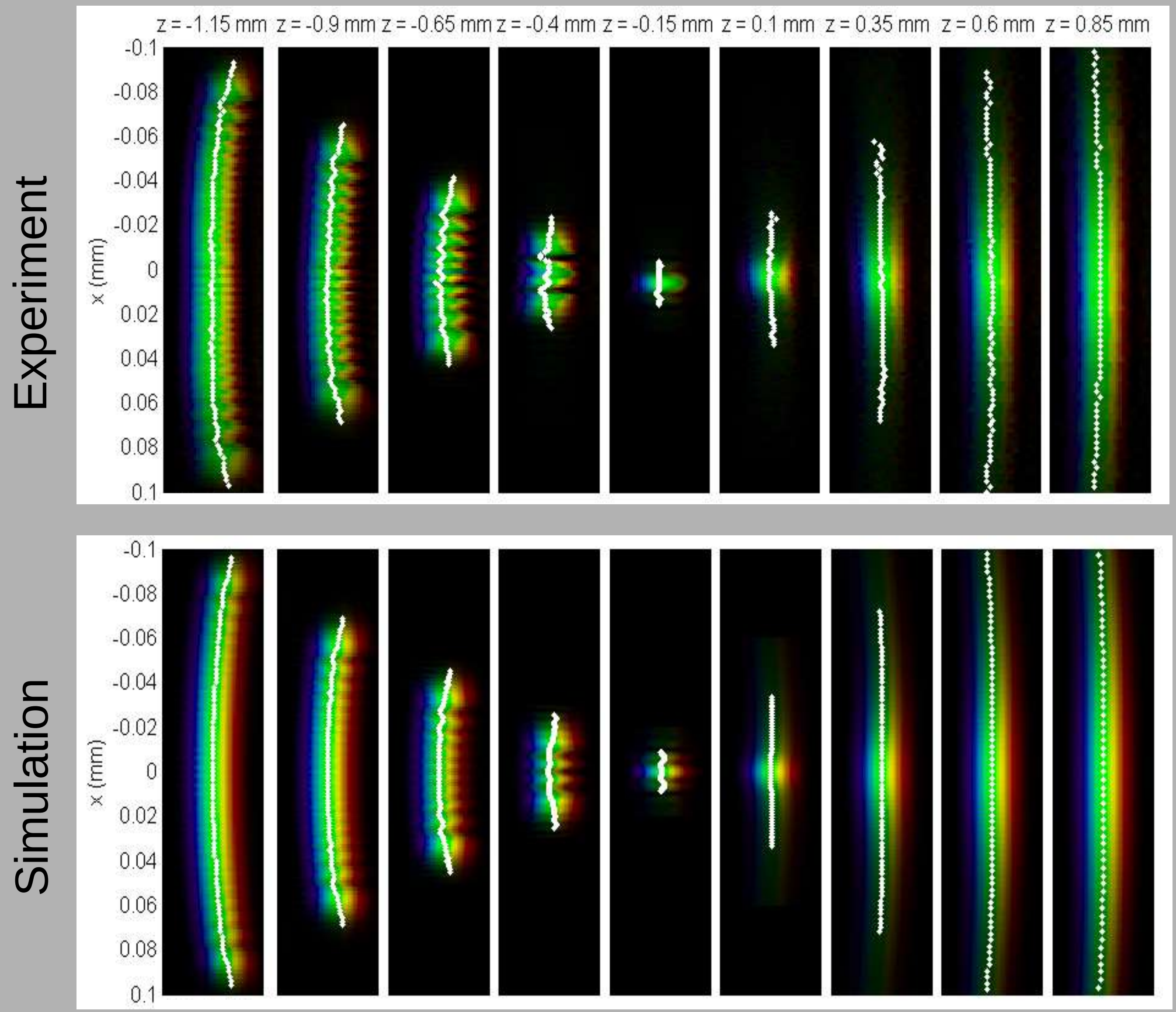
Singlet BK-7 plano-convex lens with a shorter focal length.

f = 25 mm
NA = 0.06

814 nm



787 nm

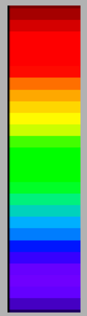


Focusing a pulse with spatial chirp and pulse-front tilt.

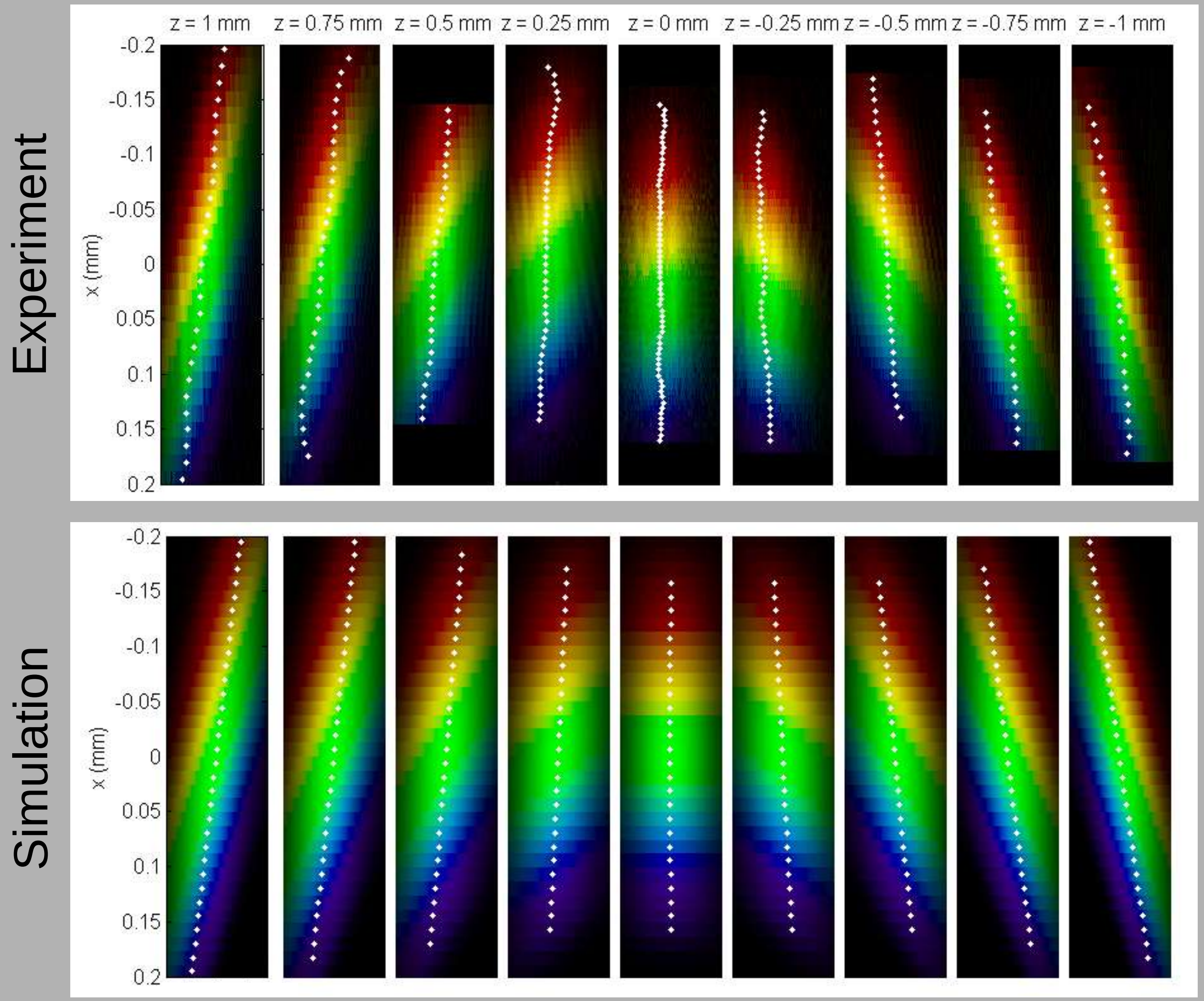
Aspheric PMMA lens.

f = 50 mm
NA = 0.03

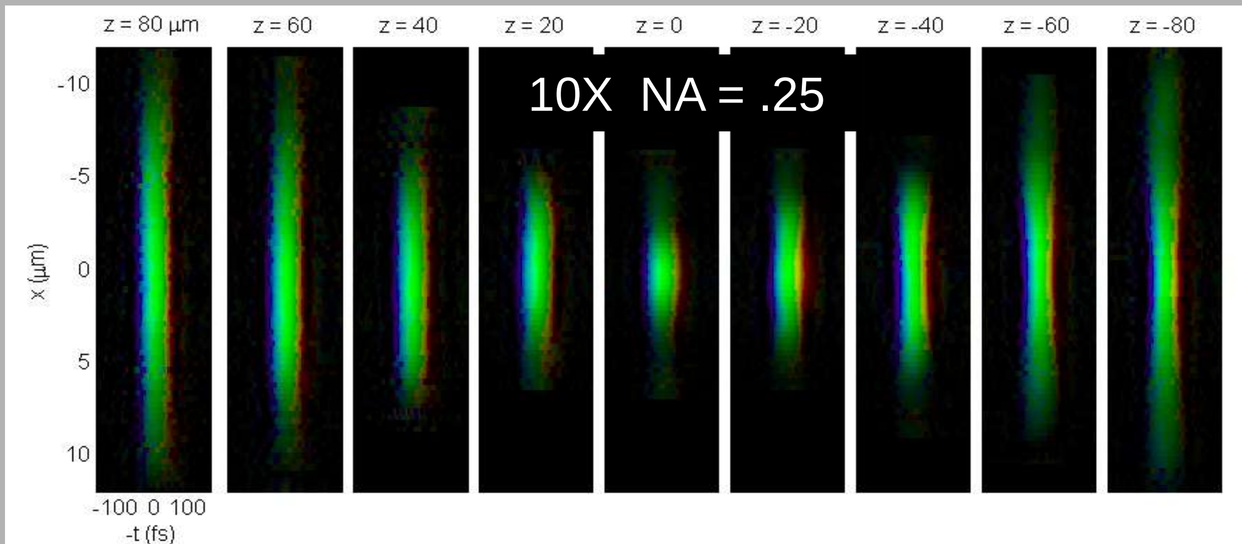
812 nm

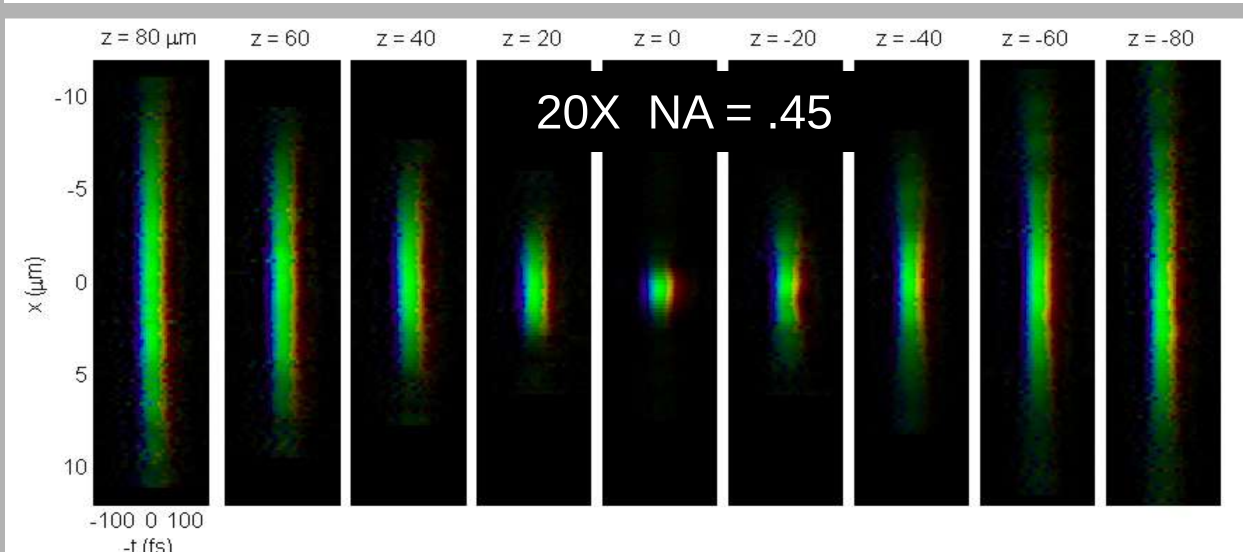


790 nm



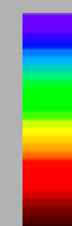
Measurements of microscope objectives using an NSOM tip





The spot size at the focus is 4µm.

789 nm



817 nm

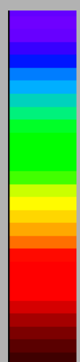
The spot size at the focus is 2µm.

Some radially varying GDD is present.

The focus of an SF11 plano-convex lens

NA = .28

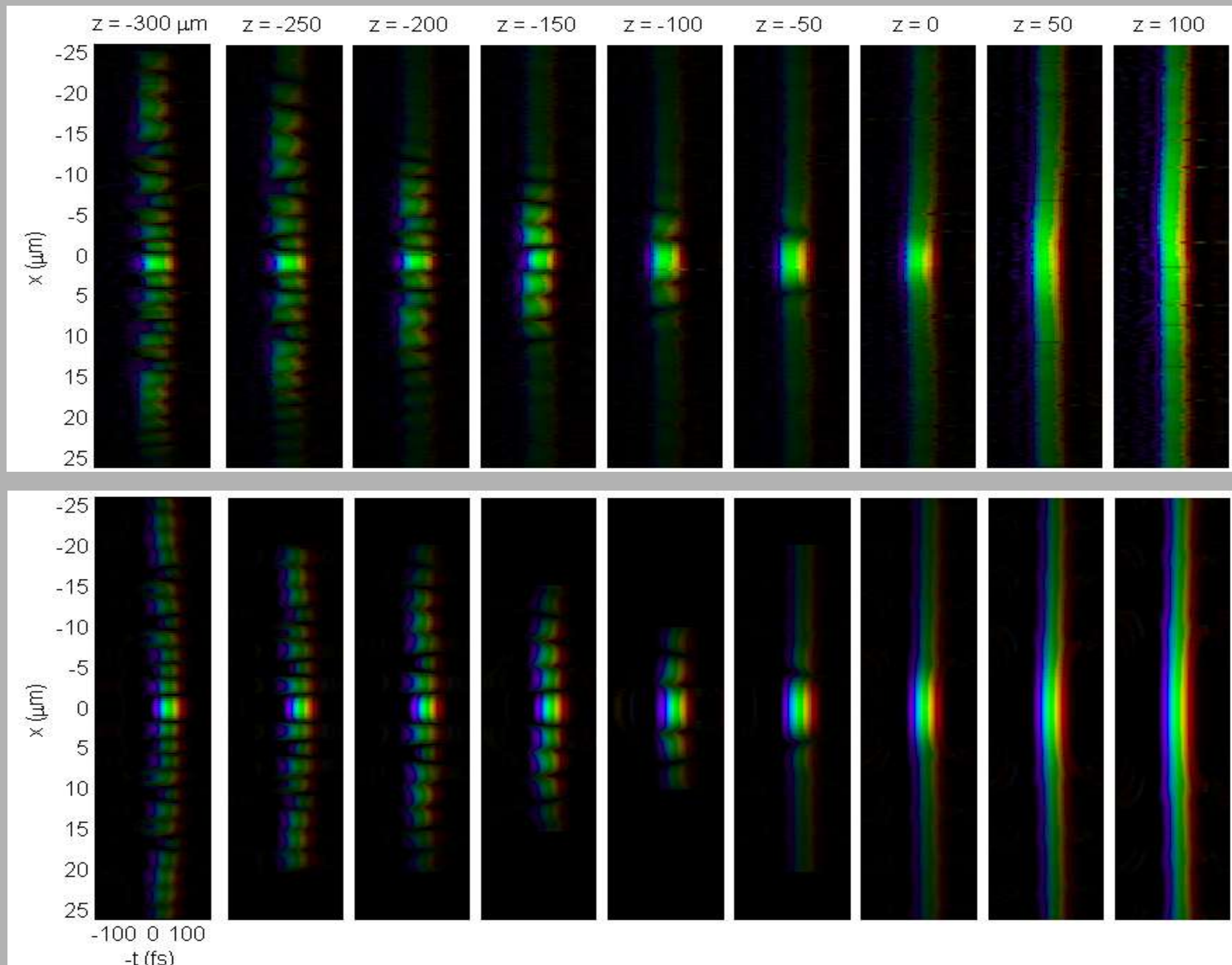
789 nm



817 nm

Experiment

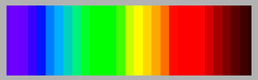
Simulation



A “fore-runner” pulse

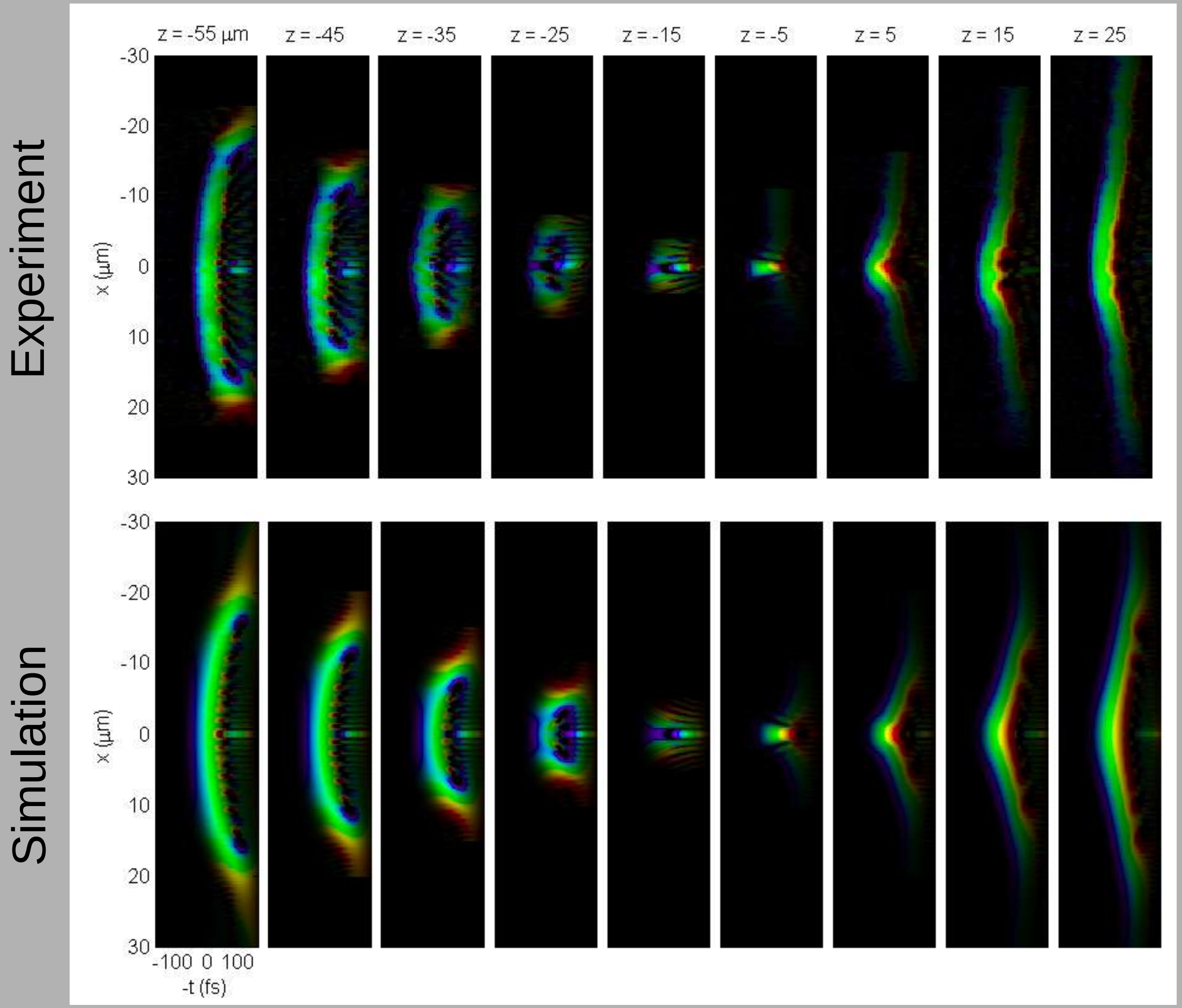
Overfilling of the lens and chromatic aberration cause an additional ”fore-runner” pulse ahead of the main pulse.

789 nm



817 nm

NA = 0.4



ELSEVIER

15 May 1996

Optics Communications 126 (1996) 185–190

OPTICS COMMUNICATIONS

Interferometric measurement of femtosecond pulse distortion by lenses

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Abstract

An interferometric method for measurement of femtosecond pulse distortion caused by lenses is described. The linear method allows measurements at low intensity with precision approaching 1 fs. Data for several high numerical aperture microscope objective lenses are presented showing single pass wavepacket distortion between 9 and 18 fs.

It has long been recognized that ultrashort light

the focus resulting in increased pulse duration and a

How NOT to make a SPIDER measurement

Remember that a separate measurement of the spectrum is required.

Step 1: Align laser for flattest spectral phase.

Step 2: Make a SPIDER measurement of the spectral phase.

Step 3: Align laser for broadest spectrum.

Step 4: Measure spectrum with a spectrometer.

If you do this, you've just cheated! You've measured the spectrum of one pulse and the spectral phase of another! You have to measure both the spectrum and spectral phase of the same pulse, that is. At the same time or at least without touching the laser between the measurements!!!

More ways NOT to make a SPIDER measurement

Remember that a separate measurement of the spectrum is required.

Step 1: Align laser for flattest spectral phase.

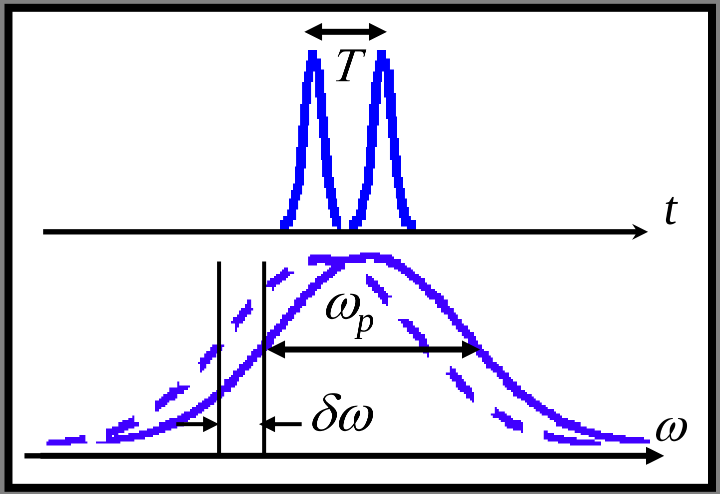
Step 2: Make a SPIDER measurement of the spectral phase.

Step 3: Align laser for the broadest ASE (amplified spontaneous emission) background or average a fine-structured jittery spectrum over many shots to smear it out.

Step 4: Measure spectrum with a spectrometer.

Again, if you do this, you've just cheated! You've measured the spectrum of one pulse and the spectral phase of another! You have to measure both the spectrum and spectral phase of the same pulse, that is, at the same time or at least without touching the laser between the measurements!!!

Accuracy of SPIDER



Recall the pulse spectral phase expansion:

$$\varphi(\omega) = \varphi_0 + \varphi_1 \cdot (\omega - \omega_0) + \frac{1}{2}\varphi_2 \cdot (\omega - \omega_0)^2 + \ldots$$

The spectral phase's key term is the ***quadratic*** one, φ_2 (the linear chirp). It's the ***linear*** term in the SPIDER phase because SPIDER measures the ***derivative*** of the pulse phase. But there's another linear term in the SPIDER phase, ωT, due to the double-pulse separation, T, which has precisely the same effect on the SPIDER trace:

$$\phi_{SPIDER} = \underbrace{\delta\omega}_{\text{frequency shear}} \frac{d\varphi}{d\omega} + \underbrace{\omega T}_{\text{pulse separation}} = \delta\omega\left[\varphi_2 \cdot (\omega - \omega_0)\right] + \omega T$$

frequency shear

pulse separation

Assuming only linear chirp and ignoring higher-order terms

Accuracy of SPIDER

Recall that $\varphi_2(\omega - \omega_0)$ is just the group delay (arrival time), τ_{gr}, of the frequency ω:

$$\phi_{SPIDER} = \delta\omega\,[\varphi_2(\omega - \omega_0)] + \omega T = \delta\omega\,\tau_{gr} + \omega T$$

So it's critical to be able to measure τ_{gr} with accuracy much better than one pulse length, τ_p. So let's get an idea of the magnitudes of the numbers involved:

$$\boxed{\phi_{SPIDER} = \underbrace{\delta\omega}_{\sim\,\omega_p/100}\,\underbrace{\tau_{gr}}_{<\,\tau_p} + \underbrace{\omega}_{>\,10\omega_p}\underbrace{T}_{\sim\,100\,\tau_p}}$$

The uninteresting term, ωT, heavily dominates (by ~10^5) the term we care about, $\delta\omega\,\tau_{gr}$.

An error in T of δT will correspond to an error in the group delay, $\delta\tau_{gr}$:

$$\delta\omega\,\delta\tau_{gr} = \omega\,\delta T \quad \text{or} \quad \delta\tau_{gr} = \frac{\omega}{\delta\omega}\,\delta T$$

SPIDER accuracy (cont'd)

$$\delta\tau_{gr} = \frac{\omega}{\delta\omega}\delta T$$

The group delay errors at the maximum and minimum frequencies in the pulse spectrum are then:

$$\left(\delta\tau_{gr}\right)_{\max} = \frac{\omega_{\max}}{\delta\omega}\delta T \qquad \left(\delta\tau_{gr}\right)_{\min} = \frac{\omega_{\min}}{\delta\omega}\delta\tau$$

The error in the pulse length is then the difference between these two group-delay errors:

$$\delta\tau_p = \frac{\omega_{\max} - \omega_{\min}}{\delta\omega}\delta T$$

or

pulse bandwidth

$$\boxed{\delta\tau_p = \frac{\omega_p}{\delta\omega}\delta T}$$

frequency shear

In terms of ratios:

$$\boxed{\frac{\delta\tau_p}{\tau_p} = \frac{\omega_p}{\delta\omega}\,\frac{T}{\tau_p}\,\frac{\delta T}{T}} = 100 \times 100 \times \frac{\delta T}{T}$$

The accuracy of the separation must be $<10^{-5}$, and really 10^{-6}! This is typically only a few attoseconds!