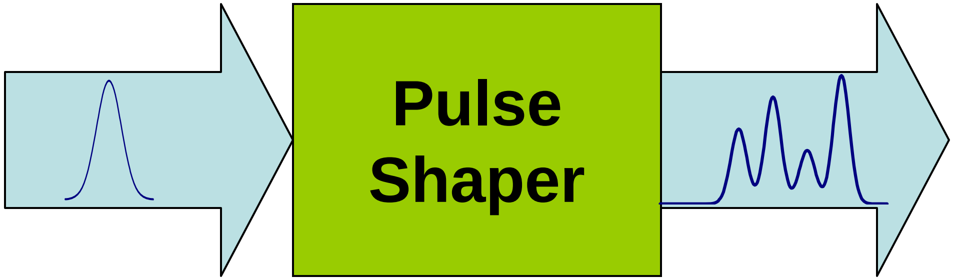
Pulse shaping



Pulse shaping: transform input pulse (usually simple) to output

Linear filter

Basic apparatus using spatial decomposition

Spatial modulators:

Liquid crystal

Acouto-optics

Micromechanical or flexible mirrors

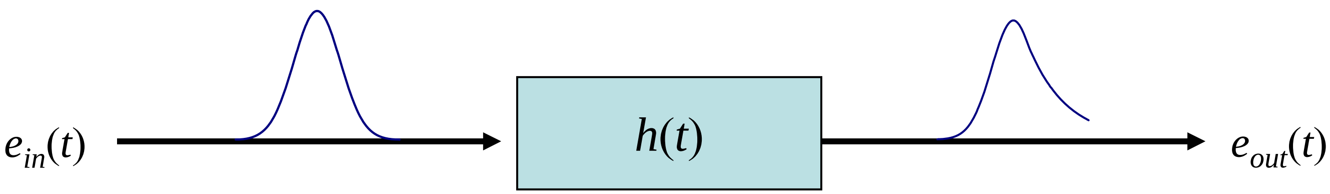
Time-to-space mapping

“Dazzler”

Basics: Linear filtering

Pulse shapers can be viewed as linear, time invariant filters

Time domain description:



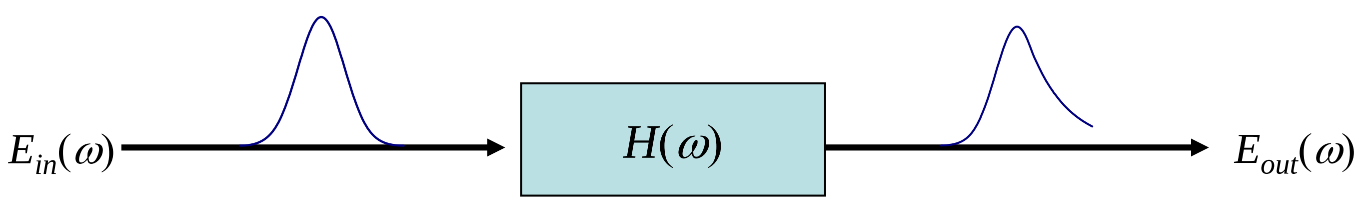
Impulse response

$$e_{out}(t) = e_{in}(t) * h(t) = \int e_{in}(t')h(t-t')dt'$$

"impulse response function" (engineers)

"Greens function" (physicists)

Frequency domain description:



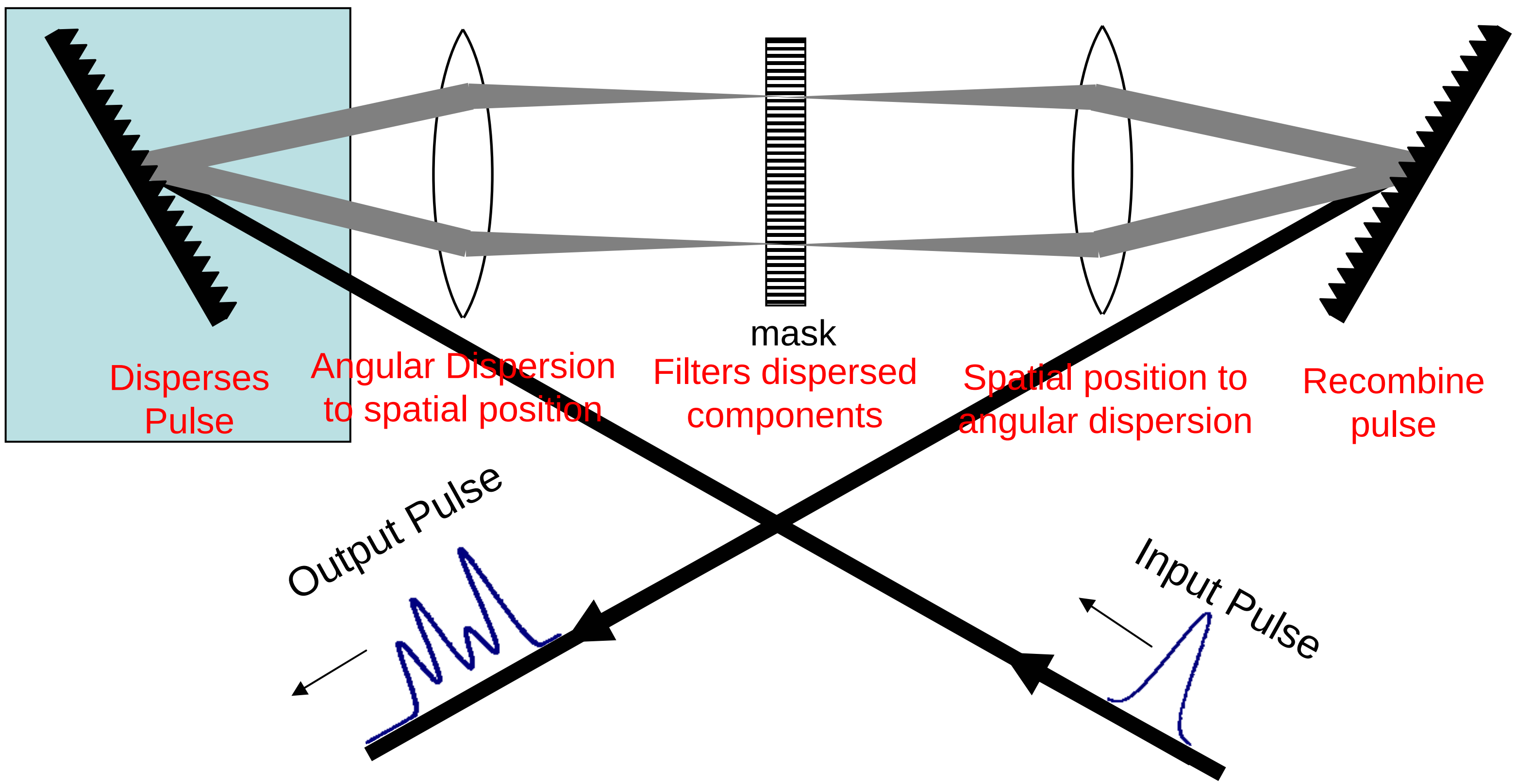
Frequency response

$$E_{out}(\omega) = E_{in}(\omega)H(\omega)$$

where

$$H(\omega) = \int h(t)e^{-i\omega t}dt$$

Basic apparatus with fixed mask



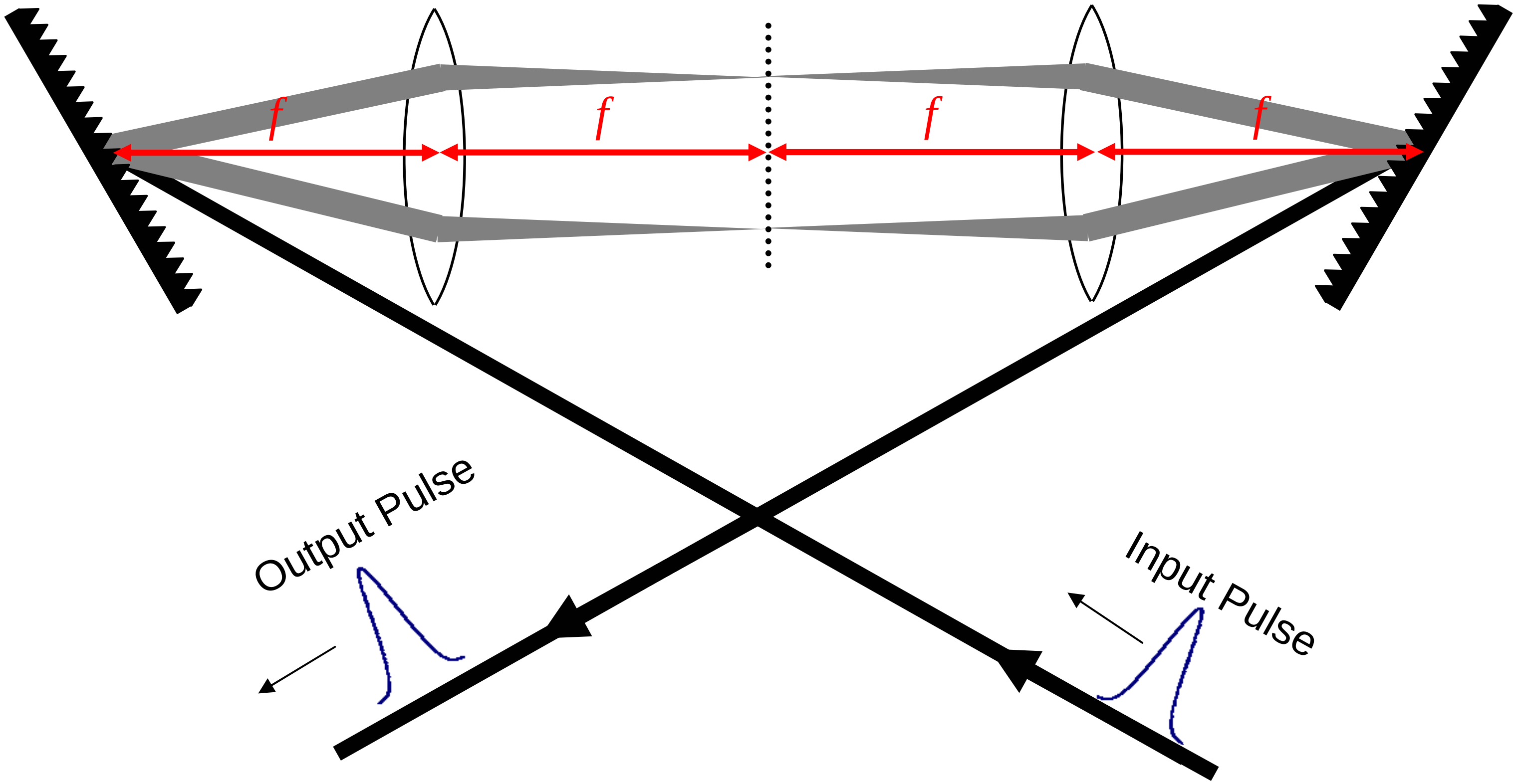
Primary components:

"zero dispersion" pulse compressor

Mask – amplitude, phase or both

Froehly, Colombeau and Vampouille, in Progress in Optics, E. Wolf, ed. (North-Holland, Amsterdam, 1983)
Heritage, Thurston, Tomlison, Weiner and Stolen, Appl. Phys. Lett. 47, 87 (1985)
Weiner, Heritage and Thurston, Opt. Lett. 11, 153 (1986)

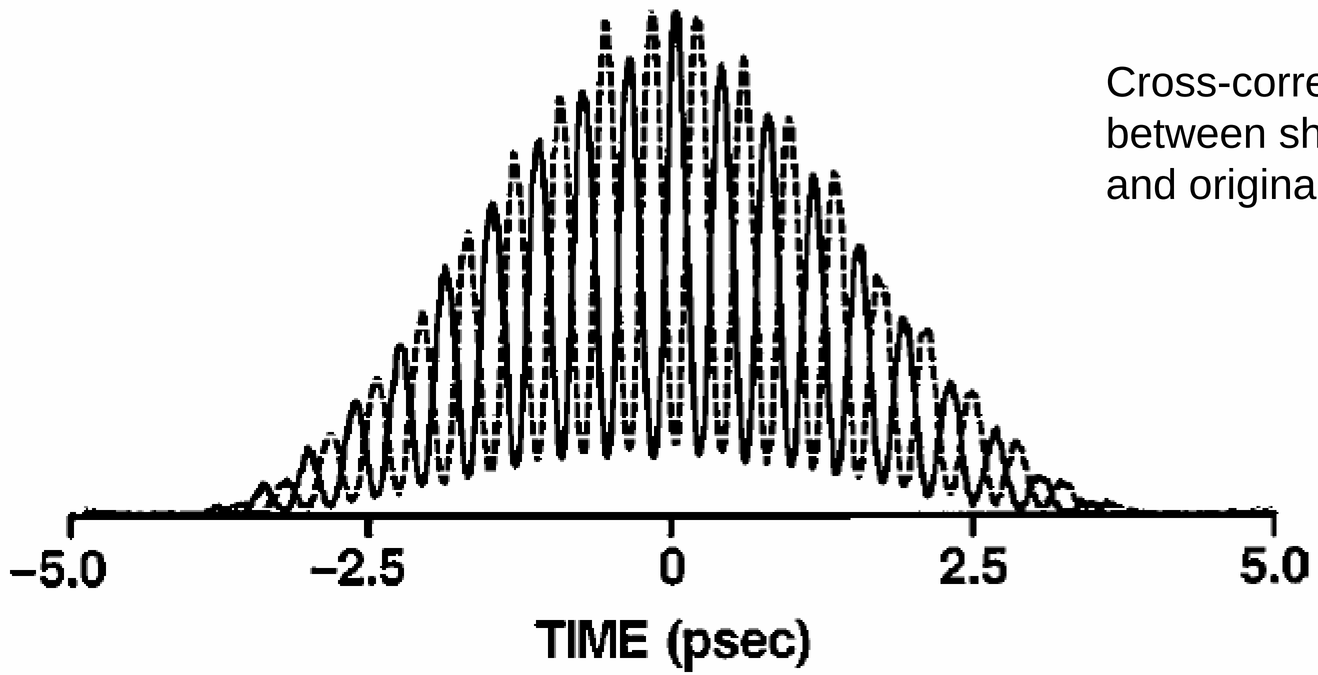
Zero dispersion compressor



Proper alignment: Output pulse identical to input pulse

- Lenses set as unit magnification telescope
  - Gratings at outside focal planes
  - Mask at internal focal plane
  - Effectively successive Fourier Transforms
- Considerations
  - Lenses must be thin and aberration free (large f number)
  - Chromatic Dispersion in Lenses
    - Lenses for pulse duration > 50 fs
    - Curved mirrors below

Simple example



Cross-correlation between shaped pulse and original pulse

Pair of optical frequencies

Mask is effectively two slits

Solid line: optical components in phase

Dashed line: optical components out of phase by π

Square pulse

If we wish to generate a square pulse

What is spectrum?

$$E(\nu) = E_0 T \frac{\sin(\pi \upsilon T)}{\pi \upsilon T}$$

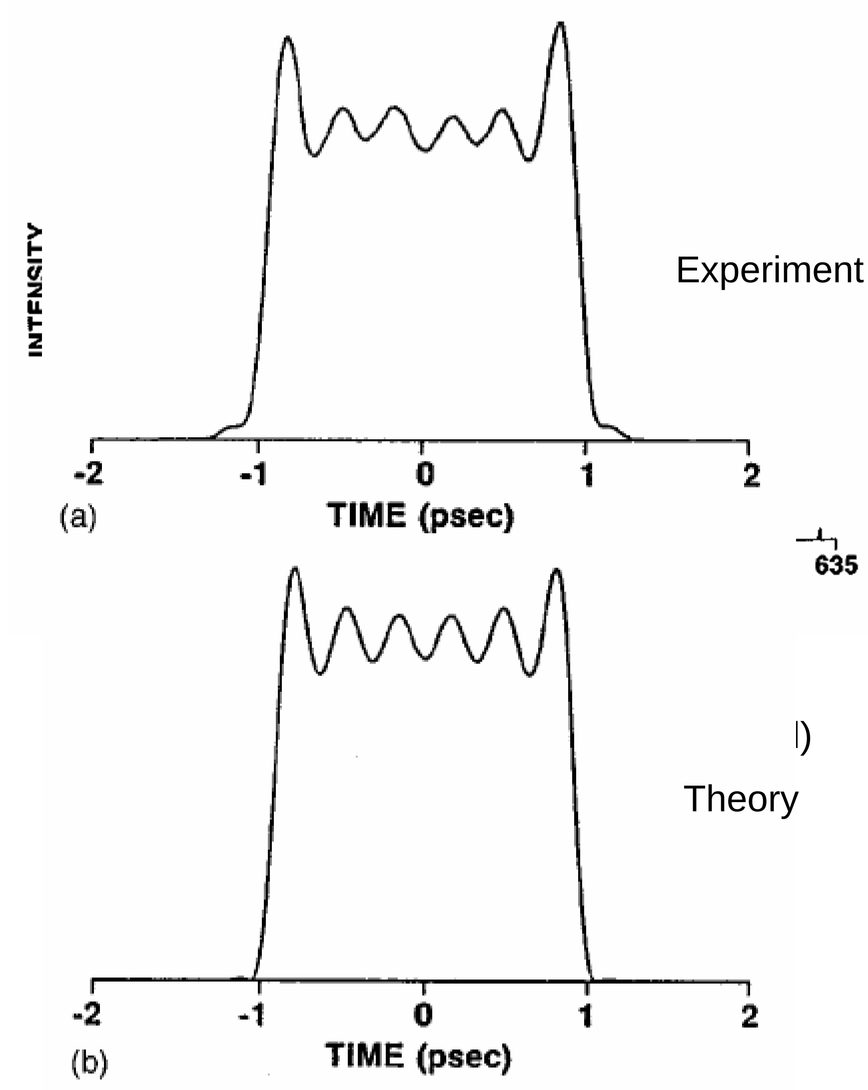
Corresponding to a mask function

$$M(x) = E_0 T \frac{\sin(\pi x / x_0)}{\pi x / x_0}$$

with

$$x_0 = \left(T \frac{\partial \nu}{\partial x} \right)^{-1}$$

where $\frac{\partial \nu}{\partial x}$ is the dispersion



Experiment

Theory

Requires phase and amplitude masks due to sign change

Ripple can be reduced at the expense of slower rise and fall

Phase only filtering

Advantage:

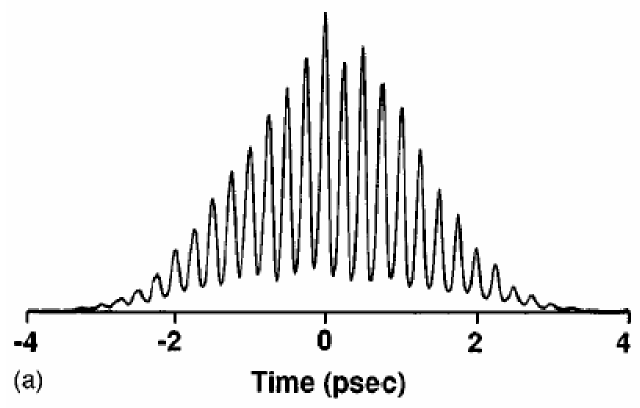
- No inherent loss

Disadvantage:

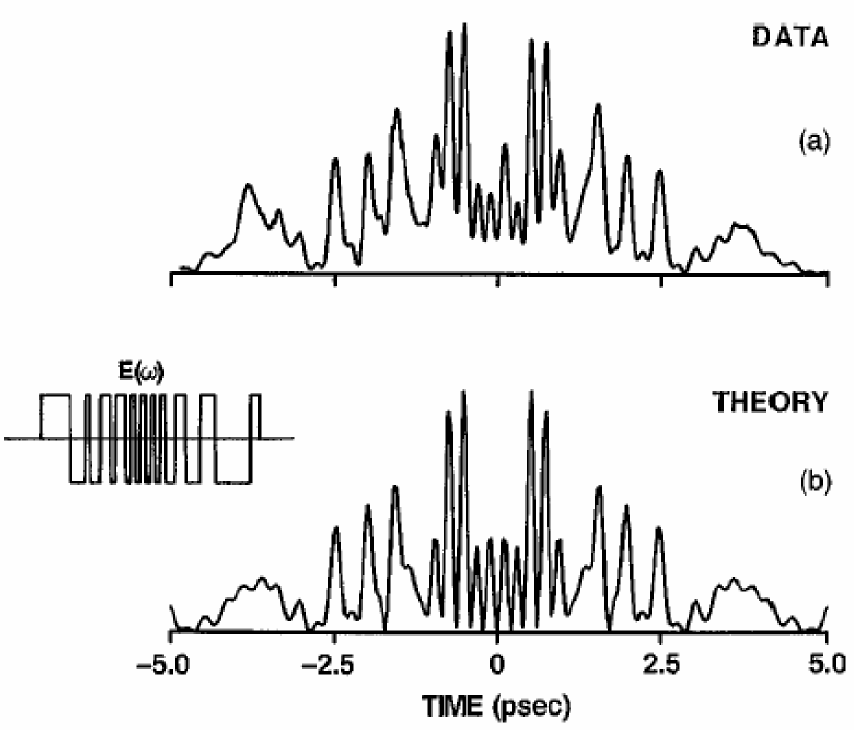
- Reduced degrees of freedom
  - But enough if only the temporal intensity profile is of interest.

Examples:

Pulse train generation
(periodic phase mask)



Pseudo random noise burst



Theoretical Analysis I

The electric field immediately after the mask is

$$E_m(x,\omega) \sim E_{in}(\omega) e^{-(x-\alpha\omega)^2 / w_0^2} M(x)$$

Due to spot size of frequency ω at mask

In general, a nonseparable function of x and ω
Because some frequencies may impinge on a step while others do not

Results in space-time coupling due to diffraction of certain frequencies

Where the spatial dispersion is

$$\alpha = \frac{\lambda^2 f}{2\pi c d \cos(\theta_d)} \qquad \text{[cm (rad/s)}^{-1}\text{]}$$

And the radius of the focused beam at the mask is

$$w_0 = \frac{\cos(\theta_{in})}{\cos(\theta_d)} \left(\frac{f\lambda}{\pi w_{in}} \right)$$

For an input beam radius of w_{in}, a grating spacing of d, light wavelength l, focal length f, input angle (at first grating) of θ_{in} and diffracted angle θ_d.

Theoretical Analysis II

The output beam is no longer Gaussian because the mask can impose arbitrary spatial dependence on it.

Full analysis: decompose into Hermite-Gaussian modes

We will assume that after the output of the pulse shaper we select out only the lowest order spatial mode (Gaussian)

- Use spatial filter – in the crudest approximation, just a circular aperature
- Couple into fiber

Yielding a spectral filter function of

$$H(\omega)=\sqrt{\frac{2}{\pi w_0^2}}\int M(x)e^{-2(x-\alpha\omega)^2/w_0^2}\,dx$$

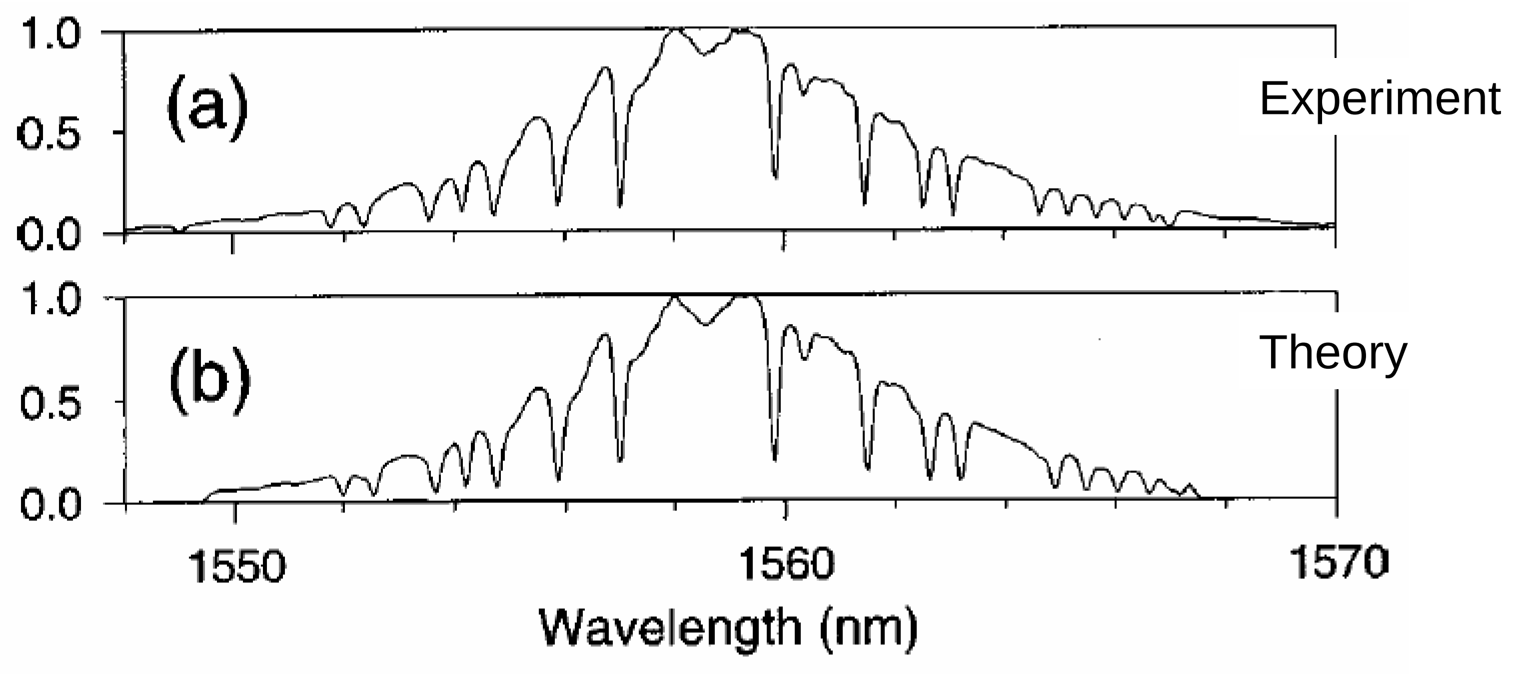
This shows that the effective filter is a convolution of the mask with the intensity profile of the beam, this limits the spectral resolution to

$$\delta\omega \cong \sqrt{\ln 2}\,\frac{w_0}{\alpha}$$

Physical features in the mask smaller than w_0 are smeared out

In addition, rapidly varying features, even in a phase mask, can diffract certain frequencies out of the beam, resulting in phase to amplitude conversion

Example of phase to amplitude coupling



Power spectrum of a waveform created by phase only mask

Dips due to phase discontinuities in mask

Theoretical Analysis III

Effect of finite spectral resolution in time domain

Fourier Transform of spectral filter function, $H(\omega)$, can be written

$$h(t) = m(t)g(t)$$

where

$$m(t) = \frac{1}{2\pi}\int M(\alpha\omega)e^{i\omega t}d\omega$$

and

$$g(t) = \exp\left(-w_0^2 t^2 / 8\alpha^2\right)$$

Infinite resolution impulse response function

Envelope function that restricts time window due to resolution

The width of the time window is

$$T = \frac{4\alpha\sqrt{\ln 2}}{w_0} = \frac{2\sqrt{\ln 2}\,w_{in}\lambda}{cd\cos\theta_{in}}$$

Proportional to number of grating lines illuminated times optical period

Complexity

The duration, δt, of the shortest temporal feature depends on bandwidth, B,

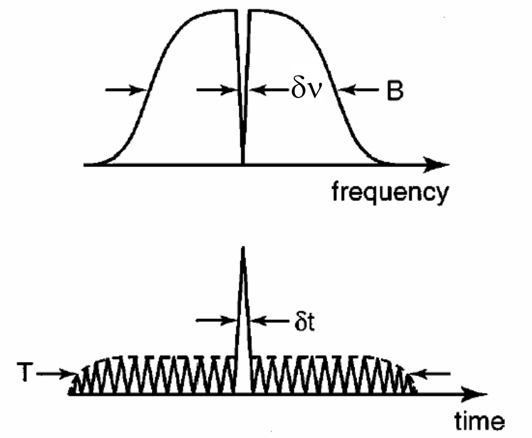
$$B \cdot \delta t \cong 0.44$$

The maximum temporal window, T, depends on spectral resolution, $\delta\nu$,

$$\delta\upsilon \cdot T \cong 0.44$$

Define the complexity as

$$\eta = \frac{B}{\delta\nu} = \frac{T}{\delta t}$$



This defines the number of

Discrete spectral features that can be put in the bandwidth

-- or --

Discrete temporal features that can be put within the time window

In terms of grating and beam parameters,

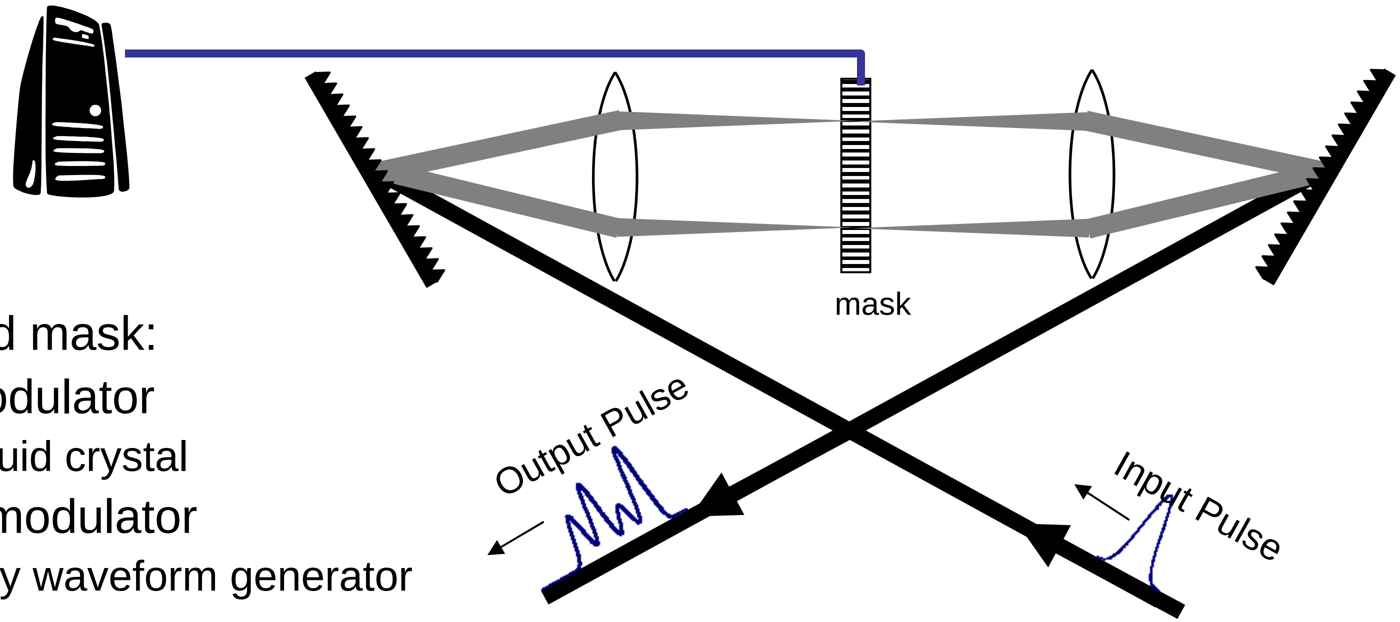
$$\eta = \frac{\Delta\lambda}{\lambda} \frac{\pi}{\sqrt{\ln 2}} \frac{w_{in}}{d\cos(\theta_{in})}$$

Numerical example:

850 nm, 1800 g/mm, 50°, 100 fs, $w_{\text{in}} = 2$ mm

T = 26.4 ps and η = 264

Automation of pulse shaping

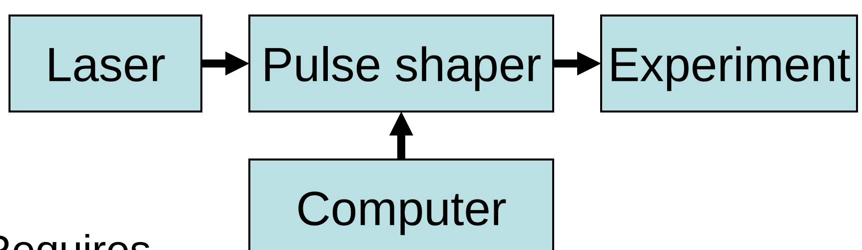


Computer controlled mask:

- Spatial light modulator
  - Typically liquid crystal
- Acousto-optic modulator
  - Use arbitrary waveform generator
- Deformable mirror

Strategies:

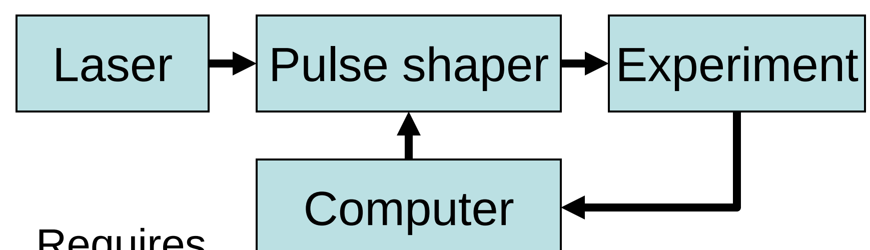
1) Open loop



Requires

- Knowledge of input pulse
  - (Less important for short input pulse)
- Careful calibration of mask & optics

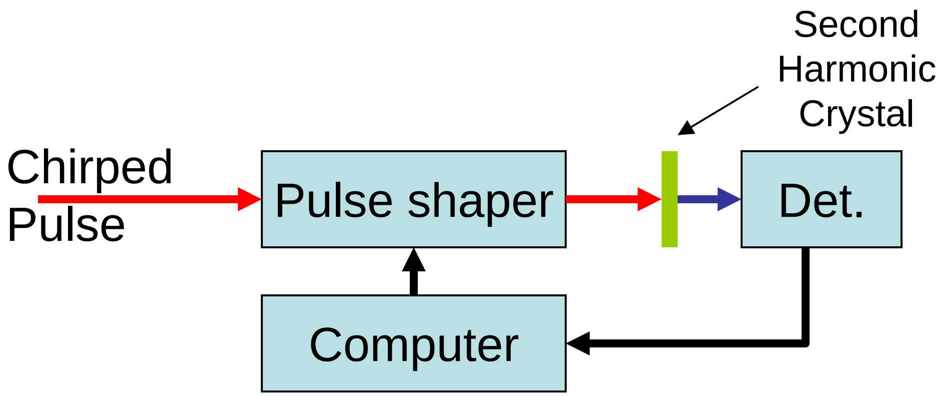
2) Closed loop

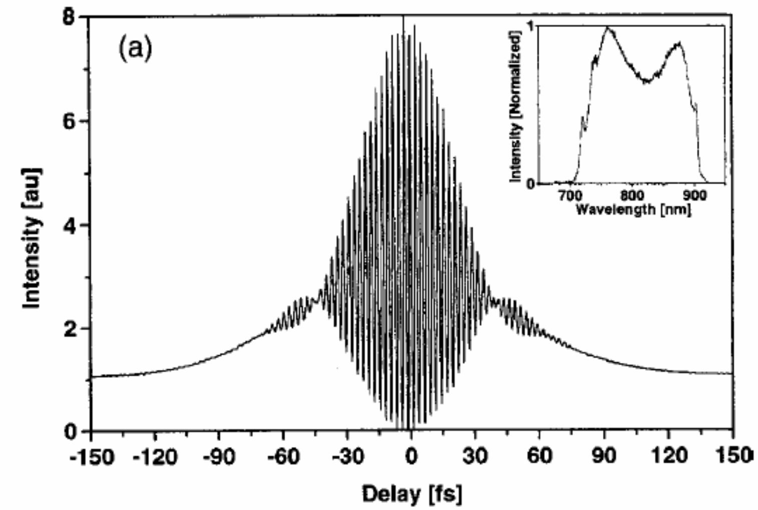


Requires

- "No" knowledge of input pulse or mask
- "Control" signal from experiment
- Algorithm for adjusting pulse shape

Example of feedback control: chirp correction





Input is chirped pulse

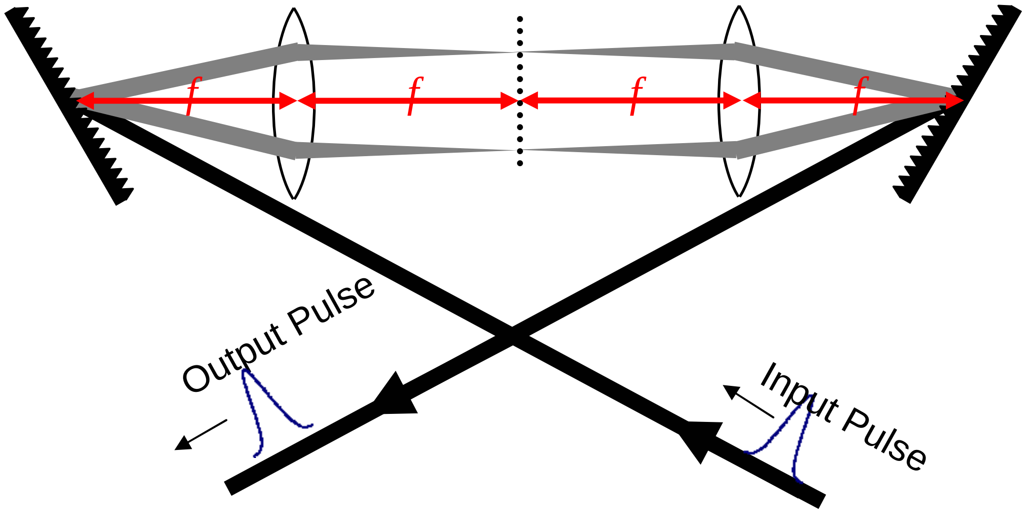
- In principle chirp is unknown
- Interferometric autocorrelation shown at above right

Computer adjust phases to maximize intensity of generated second harmonic

- Shortest pulse → highest peak intensity → shortest pulse
- Resulting "compressed pulse" autocorrelation shown at right

Yelin, Meshulach, and Silberberg, Opt. Lett. **22**, 1793 (1997)

Alignment sensitivity



The deviation from a net length of $4f$ determines the group-velocity dispersion

$$\frac{\partial^2 \phi(\omega)}{\partial \omega^2} = \frac{\lambda^3 (L - 4f)}{2\pi c^2 d^2 \cos^2 \theta_d}$$

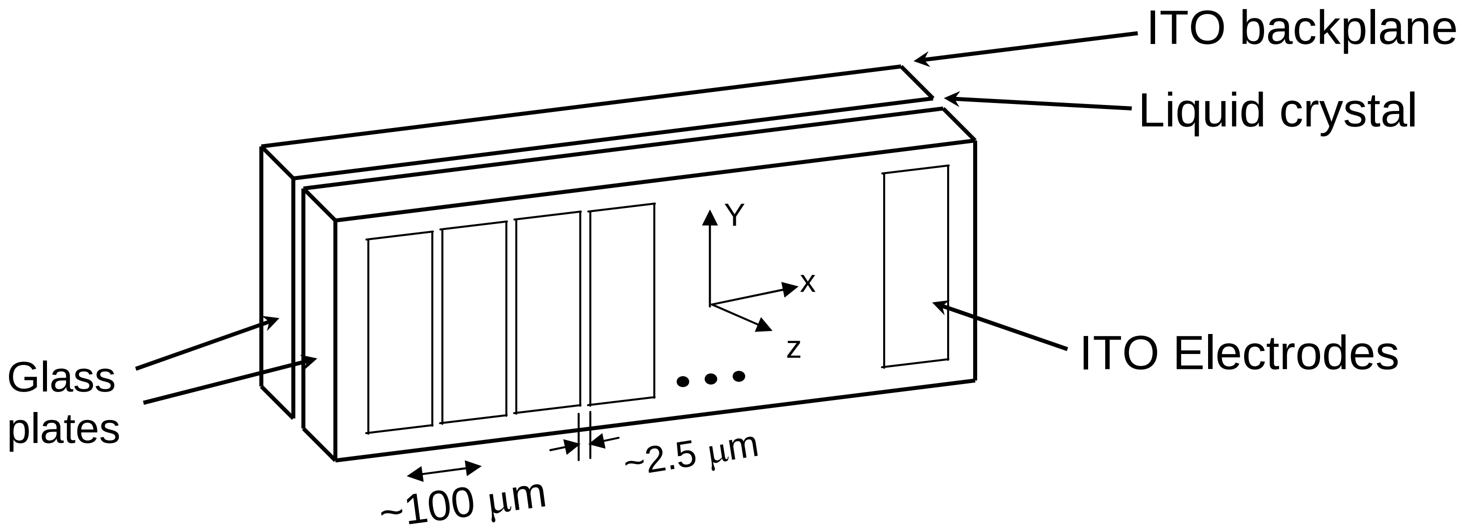
$$\frac{\partial T(\lambda)}{\partial \lambda} = \frac{\lambda (L - 4f)}{c d^2 \cos^2 \theta_d}$$

Numbers:
- 800 nm
- 1800 g/mm
- 50^{o} diffraction angle

$$\frac{\partial T(\lambda)}{\partial \lambda} = 21 \frac{\text{fs}}{\mu\text{m}}$$

Need f accurate to within
About 5 μm for a 10 fs pulse

Liquid crystal spatial light modulator (SLM)



Nematic liquid crystal

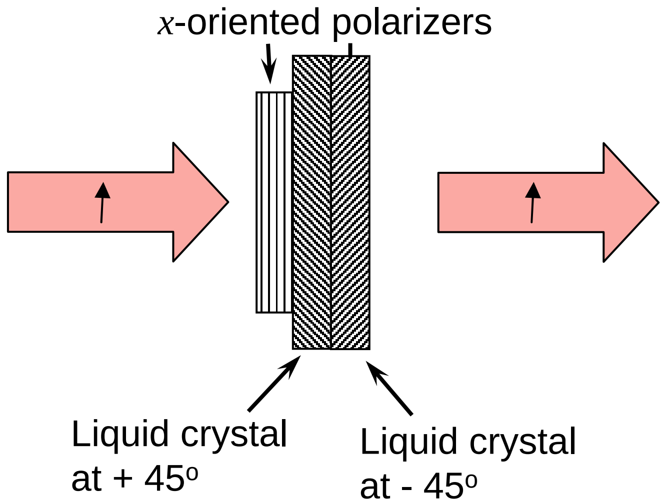
- Long thin rod like molecules
  - No electric field: aligned along y-axis
  - Electric field: rotate toward z-axis
- →Index of refraction for y-polarized light is controlled by electric field
  - Bipolar square wave drive
    - n independent of sign
    - Prevents electromigration

Transparent electrodes: indium tin oxide (ITO)

- "Front" side pixelated, 50-100 μm pitch, 2.5 μm gap
- Individually addressable
- 100s to 1000 pixels

Switching time ~ 1 ms (physical rotation of molecules in liquid)

Amplitude and Phase Modulation



A liquid crystal SLM is a phase modulator for y-polarized light

Rotate by 45° → electrically controlled wave plate

Sandwiched between polarizers it becomes an amplitude modulator

Amplitude and phase at the same time?

Sandwich two LC SLMs, rotated by 90 degrees from each other

Output field of SLMs (w/o polarizers) is

$$\mathbf{E}_{out} = E_{in} \exp\left[\frac{i\left(\Delta\phi_1 + \Delta\phi_2\right)}{2}\right]\left[\mathbf{x}\cos\left(\frac{\Delta\phi_1 - \Delta\phi_2}{2}\right) + i\mathbf{y}\sin\left(\frac{\Delta\phi_1 - \Delta\phi_2}{2}\right)\right]$$

Phase corresponds to sum of voltage applied to two modulators

Amplitude corresponds to difference

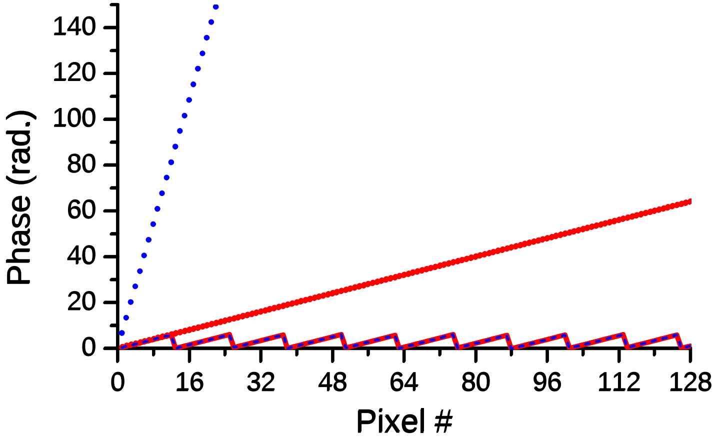
Effect of pixellation

Consider a simple case: a time shifter

To impose a time shift, we need to impose a linear phase with frequency

$$\tau = -\frac{\delta\phi}{2\pi\delta f}$$

Where δf is the phase step per pixel and $\delta\phi$ is the frequency change from one pixel to the next.



The phase is only meaningful modulo 2π

→Ambiguity by delay of $1/\delta f$

This ambiguity means that replicas occur spaced by $1/\delta f$

$$e_{out} \sim \left[e_{in}(t) * \sum_n h\left(t - n\frac{1}{\delta f} \right) \right] \mathrm{sinc}(\pi \delta f\, t)$$

Real impulse response function has replicas, weighted by sinc function

If $h(t)$ is only non zero for small *t* (compared to $1/\delta f$), just get weak replicas, but if $h(t)$ is extended, replicas can blend into one-another.

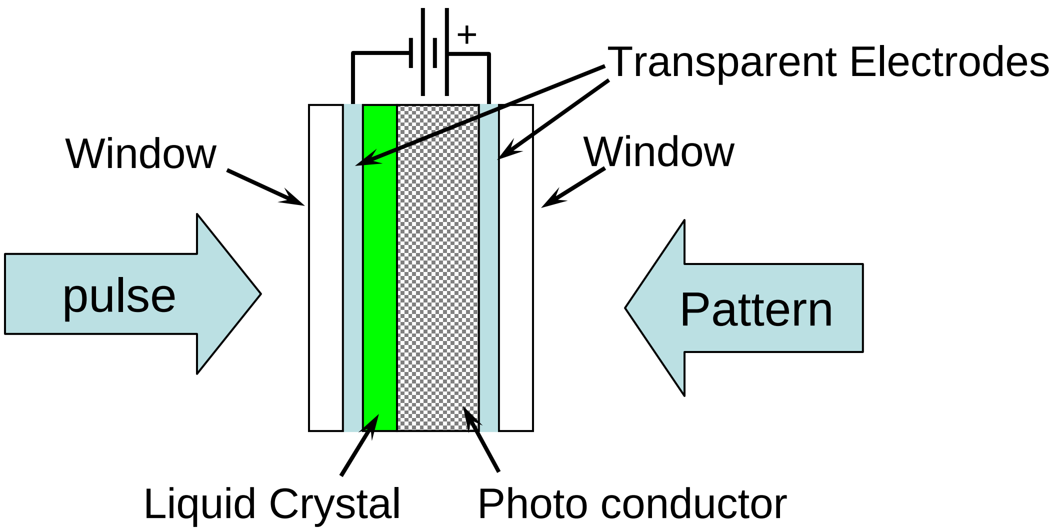
Finite spot size at the mask can also suppress replicas (gaussian time-window)

Decreasing resolution (increasing spot-size) reduces effect of pixellation

Optically Addressed Liquid Crystal SLM

Pixellation can be eliminated by using an optically addressed SLM

- Continuous device
- Pixellation in original pattern eliminated by “blurring”

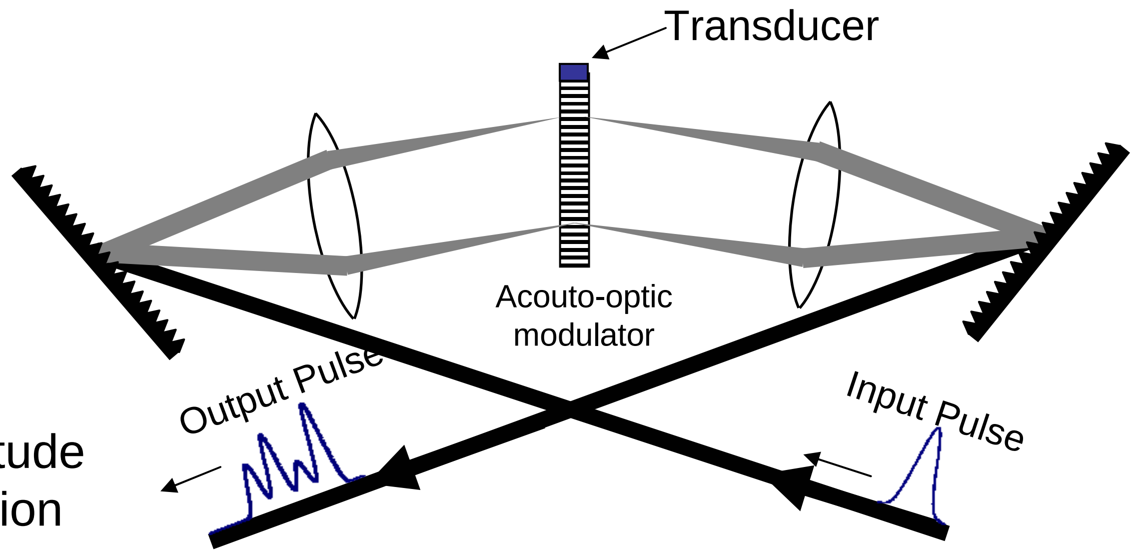


Apply DC voltage across liquid crystal + photoconductor

- Conductivity change of photoconductor upon illumination results in voltage change across liquid crystal
- Image in “pattern” light appears in index of refraction of liquid crystal
- Generation of pattern:
  - Image a CRT
  - Pass laser through 2D liquid crystal SLM

Device usually used in reflection

Acousto-optic modulator based pulse shaping I



An acoustic wave periodically modulates the index of refraction → looks like a diffraction grating

Due to speed of sound, amplitude modulation → spatial modulation

$$v_{ac} \sim 4.2 \text{ mm/}\mu\text{s}$$

Although the pattern is "frozen" during one pulse, it will move between pulses

If all pulses are to be shaped identically, must wait and reload pattern

→Wait a few μs (for ~ cm size AOM aperture)

Complexity limited by number of independent acoustic features

$$\eta \sim \Delta f \tau_0 = \frac{\Delta f \, l_a}{v_{ac}}$$

Where Δf is the modulation bandwidth of the AOM, τ_0 is its aperture time, l_a is aperture length

$$\eta \sim 900$$

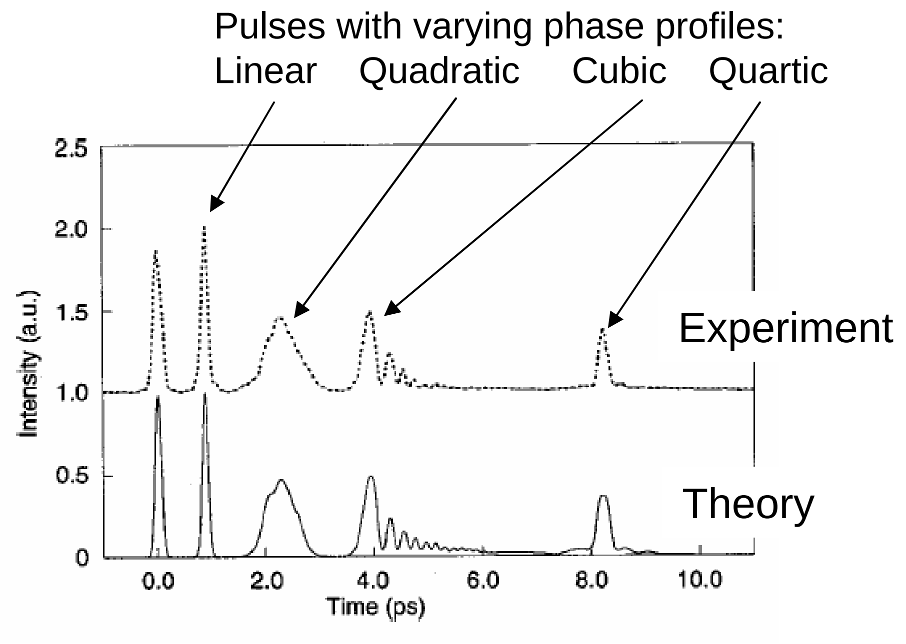
Acousto-optic modulator based pulse shaping II

Use "arbitrary waveform generator" (AWG) to produce complex RF waveform

Typically run AWG at "baseband" and use mixer to combine with carrier

Relative phase of carrier determines relative phase of diffracted light

Example of complex waveform:



Issues of AOM cell thickness

Thin: poor diffraction efficiency

Thick: good diffraction efficiency, depth of focus is an issue

Acoustic issues:

Attenuation ($\sim f^2$)

Nonlinearity → keep acoustic power low, hurts efficiency

Comparison, pulse shaping with liquid crystal versus AO modulators

	Liquid Crystal	Acousto-optic
Pulse width (tested)	> 13 fs	> 50 fs
Reprogramming time	ms	μs
Repetition rate	no limit (static shape)	< few MHz
Modulation	gray level amp & phase	gray level amp & phase
η	# pixels	~ 1000
Efficiency	High	10-15%
Fidelity	High, sidelobes	High, acoustic atten.
Technology	Custom, low freq.	Standard, high freq. RF
Ease of control	Requires calib	In principle, calibration not needed, in reality it is

Deformable mirror pulse shaper

Use "half" of pulse shaper, place deformable mirror at mask plane

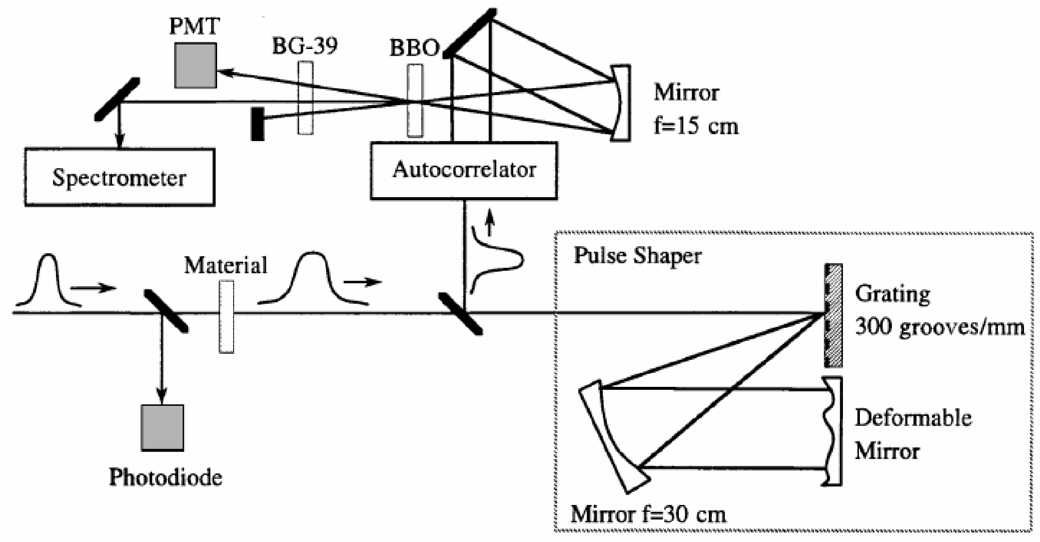
Reflect back through half pulse shaper, pick off pulse (beam splitter or slight vertical deflection)

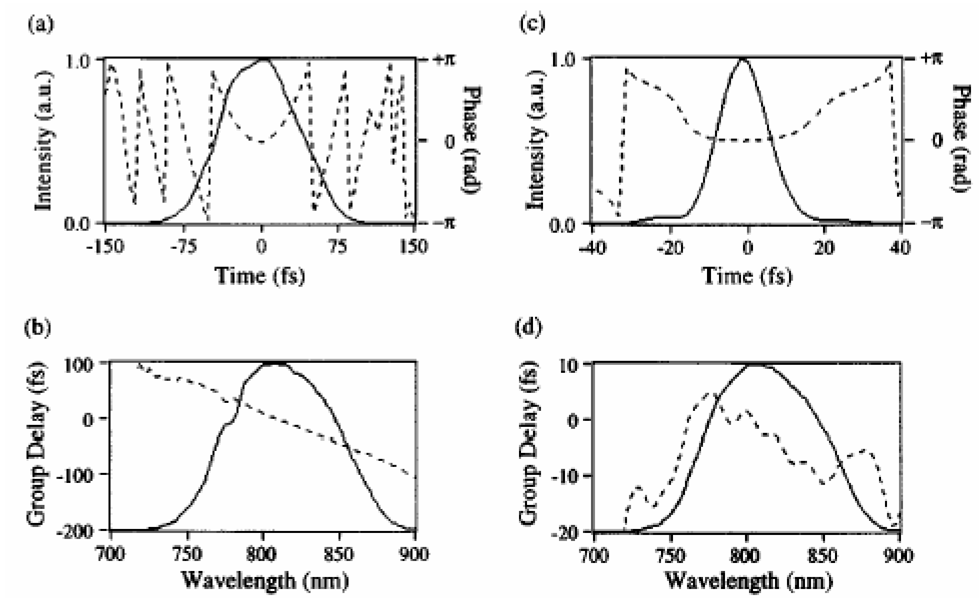
Deformation of mirror changes path length → change in phase

Good for very short pulses (no dispersive material at all)

Limits to

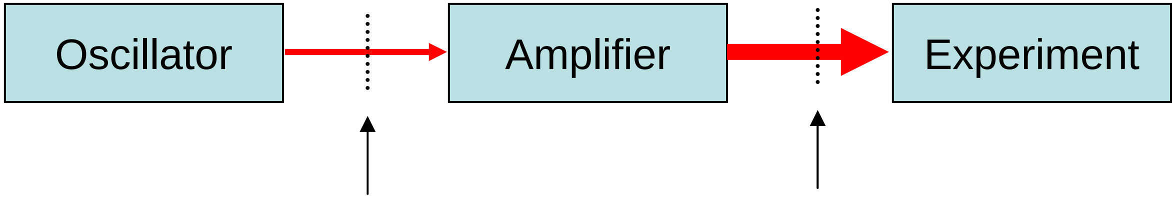
- Deflection
- # actuators
- resolution





Zeek, Maginnis, Backus, Russek, Murnane, Mourou, Kapteyn, Vdovin, Opt. Lett. **24**, 493 (1999)

Pulse shaping and amplification



Put the pulse shaper here or here ?

Between oscillator and amplifier:

Good: amplifier can usually make up for losses in shaper

Bad: nonlinearity (& dispersion) in amplifier can distort pulse

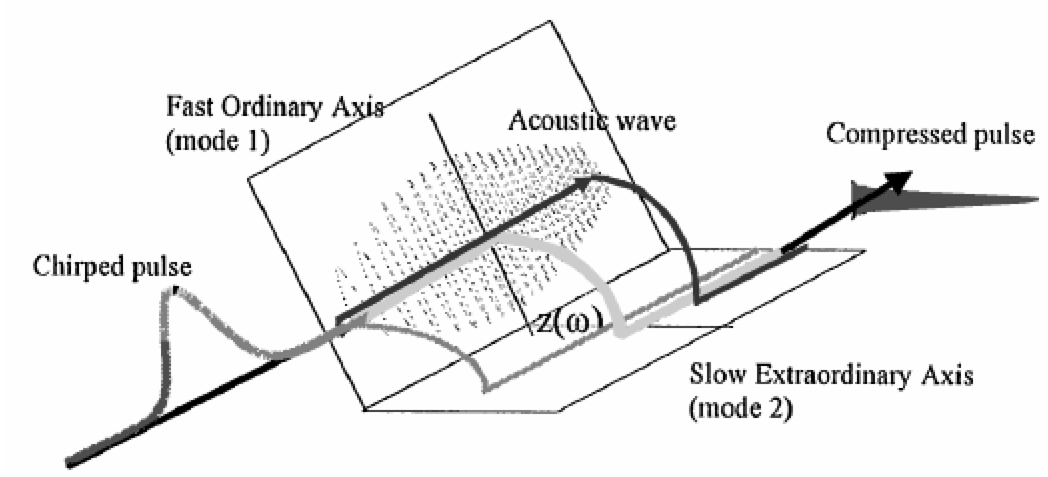
Maybe correct by measuring pulse after amplifier and precompensating

Between amplifier and experiment:

Good: No distortion by amplifier

Bad: Punching holes in your modulator

Acousto-optic programmable dispersive filter I



Co-propagating optical and acoustic waves in birefringent material (TeO_2)

Acoustic wave couples power between axes

Frequency of couple light depends on acoustic frequency (phase matching)

Difference in propagation speeds allow programmable group delay

$$E_{out}(t) \propto E_{in}(t) \otimes S(t/\alpha)$$

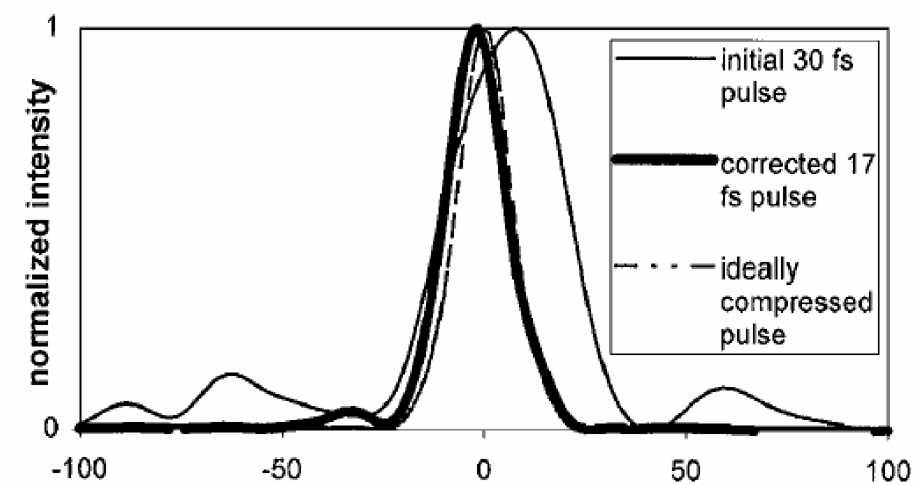
Where $S(t)$ is the electrical signal and $\alpha = \Delta n(v/c)$

Verluise, Laude, Cheng, Spielmann and Tournois, Opt. Lett. **25**, 575 (2000).

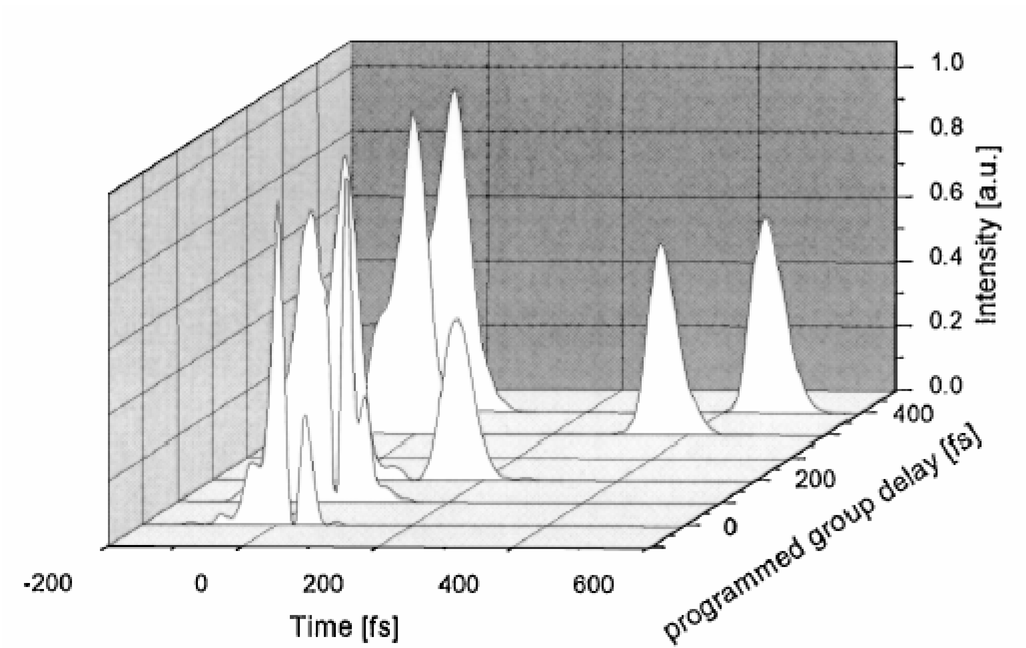
Acousto-optic programmable dispersive filter II

Examples:

Chirp correction



Programmable pulse pair



Verluise, Laude, Cheng, Spielmann and Tournois, Opt. Lett. **25**, 575 (2000).