ULTRAFAST OPTICS

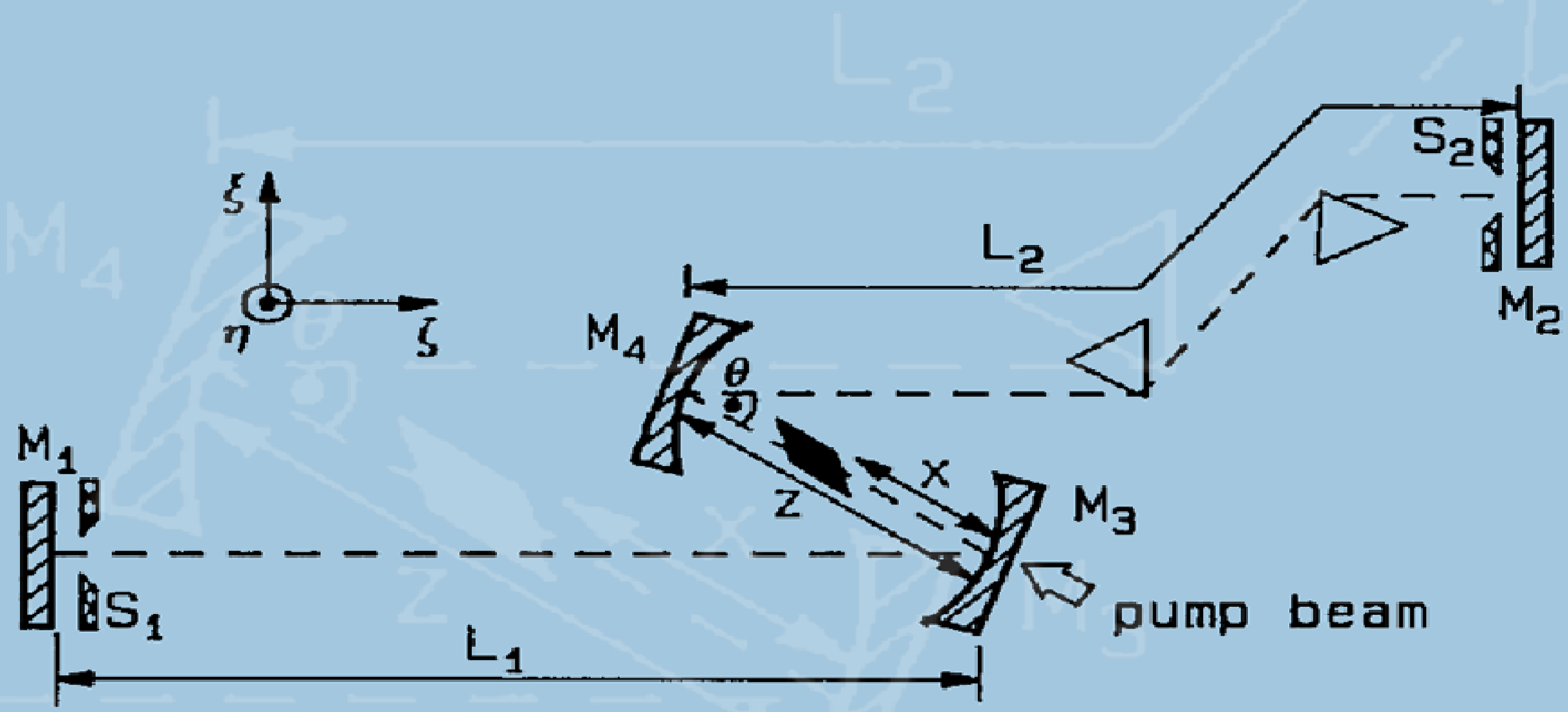


image from G. Cerullo et al., Opt. Lett. 19, 807 (1994), © OSA

by PIOTR WASYLCZYK

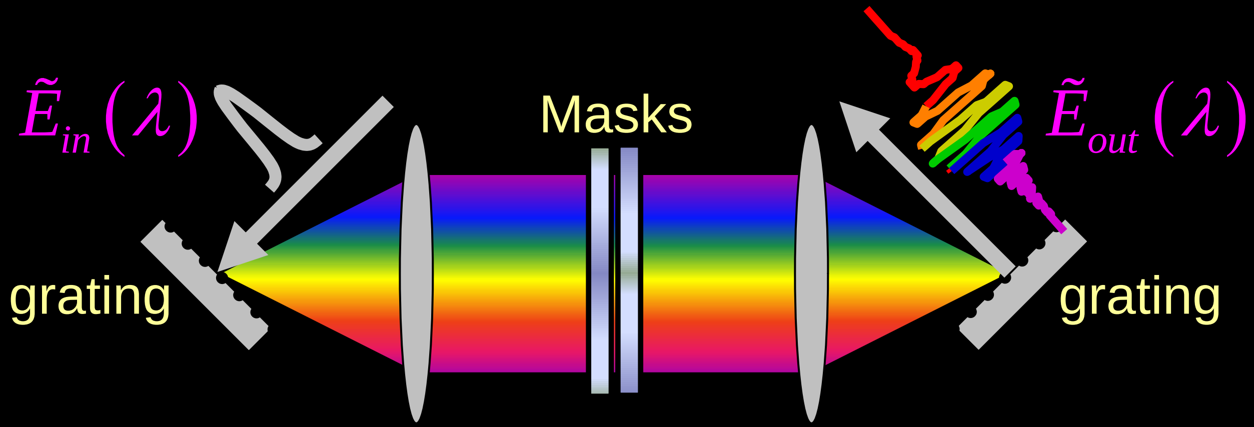
Pulse Shaping

What do we mean by pulse shaping and why do we care about it?

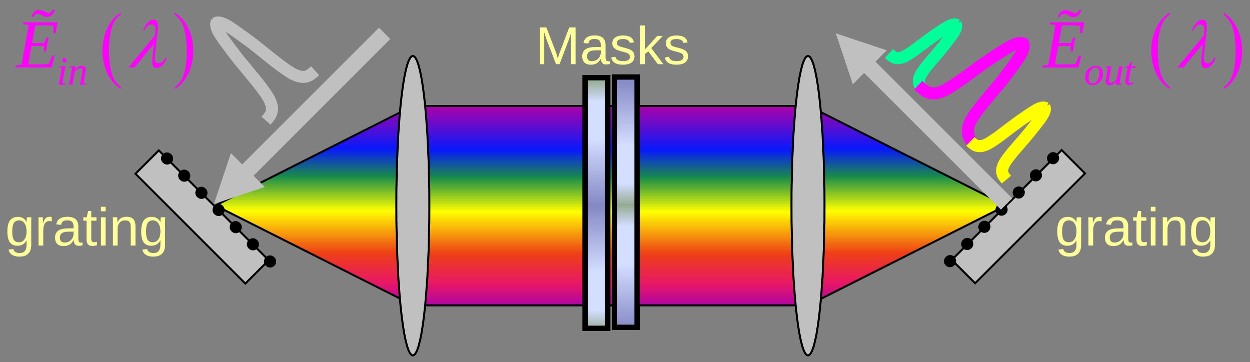
Methods of pulse shaping
- Fourier synthesis
  - Spatial-light modulators
  - Acousto-optic modulators
  - Deformable mirrors
- Acousto-optic shaping

Phase-only pulse shaping
- Genetic algorithms
- Simulated annealing

Adaptive pulse-shaping



Why pulse-shape?



To compress pulses with complex phase

To generate pulses that control chemical reactions or other phenomena

To generate trains of pulses for telecommunications

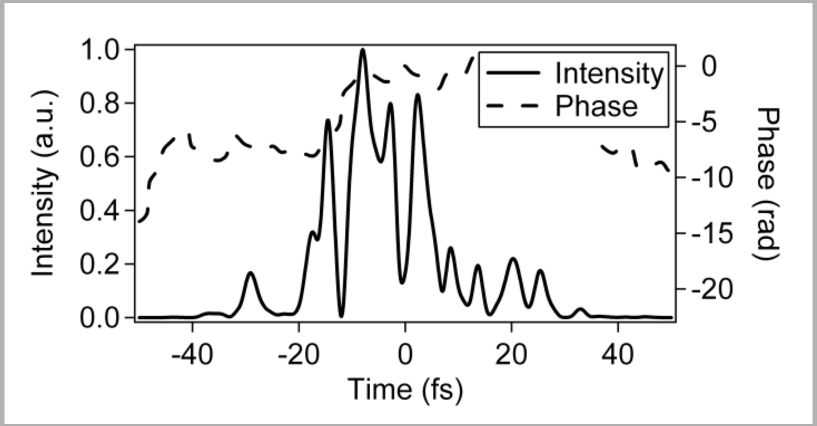
To precompensate for distortions that occur in dispersive media

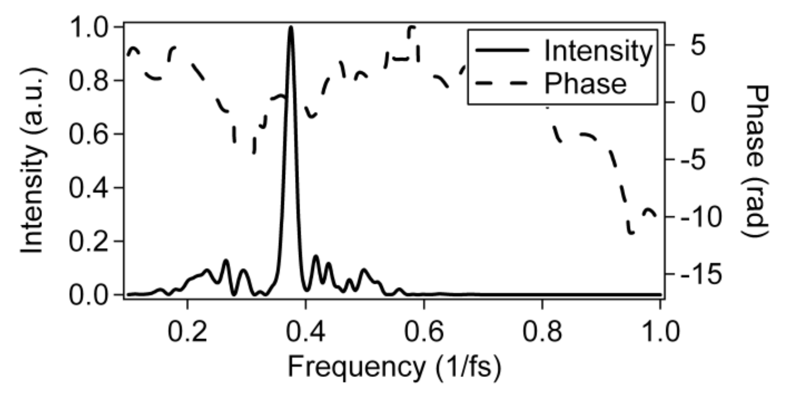
Pulse shaping: a loose definition

Loosely defined: Pulse shaping includes anything that changes the pulse shape.

Recall that a pulse is defined by its intensity and phase in either the time or frequency domain.

$$E(t) = \sqrt{I(t)}e^{-i\phi(t)} \qquad \tilde{E}(\omega) = \sqrt{S(\omega)}e^{-i\varphi(\omega)}$$

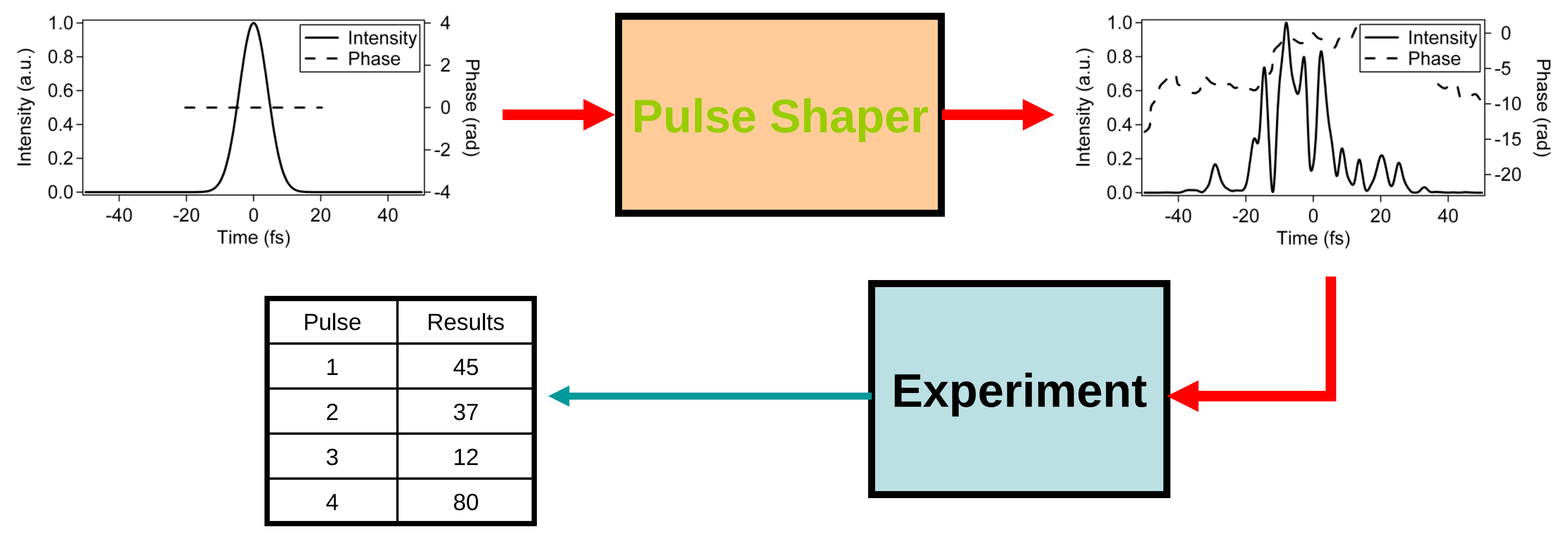




Altering any of pulse’s parameters changes the pulse.

What do we really mean by pulse shaping?

Tailoring a pulse shape in a specific controlled manner.



Pulse	Results
1	45
2	37
3	12
4	80

By changing the pulse shape we can alter the results of an experiment.

How do we modulate an ultrashort pulse?

We could try to modulate the pulse directly in time.

$$E_{out}(t) = h(t)E_{in}(t)$$

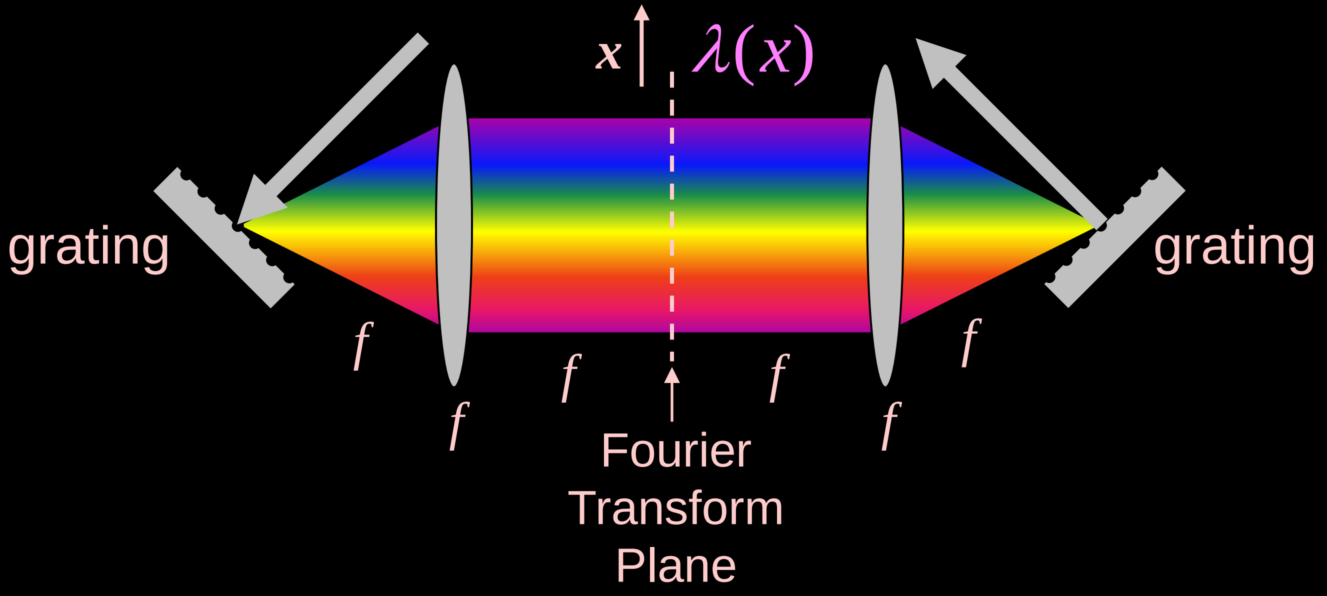
Unfortunately, modulators are too slow.

Alternatively, we can modulate the spectrum.

$$\boxed{\tilde{E}_{out}(\omega) = H(\omega)\tilde{E}_{in}(\omega)}$$

So all we have to do is to frequency-disperse the pulse in space and modulate the spectrum and spectral phase by creating a spatially varying transmission and phase delay.

An all-optical Fourier transform: the zero-dispersion stretcher



How it works:

The grating disperses the light, mapping color onto angle.

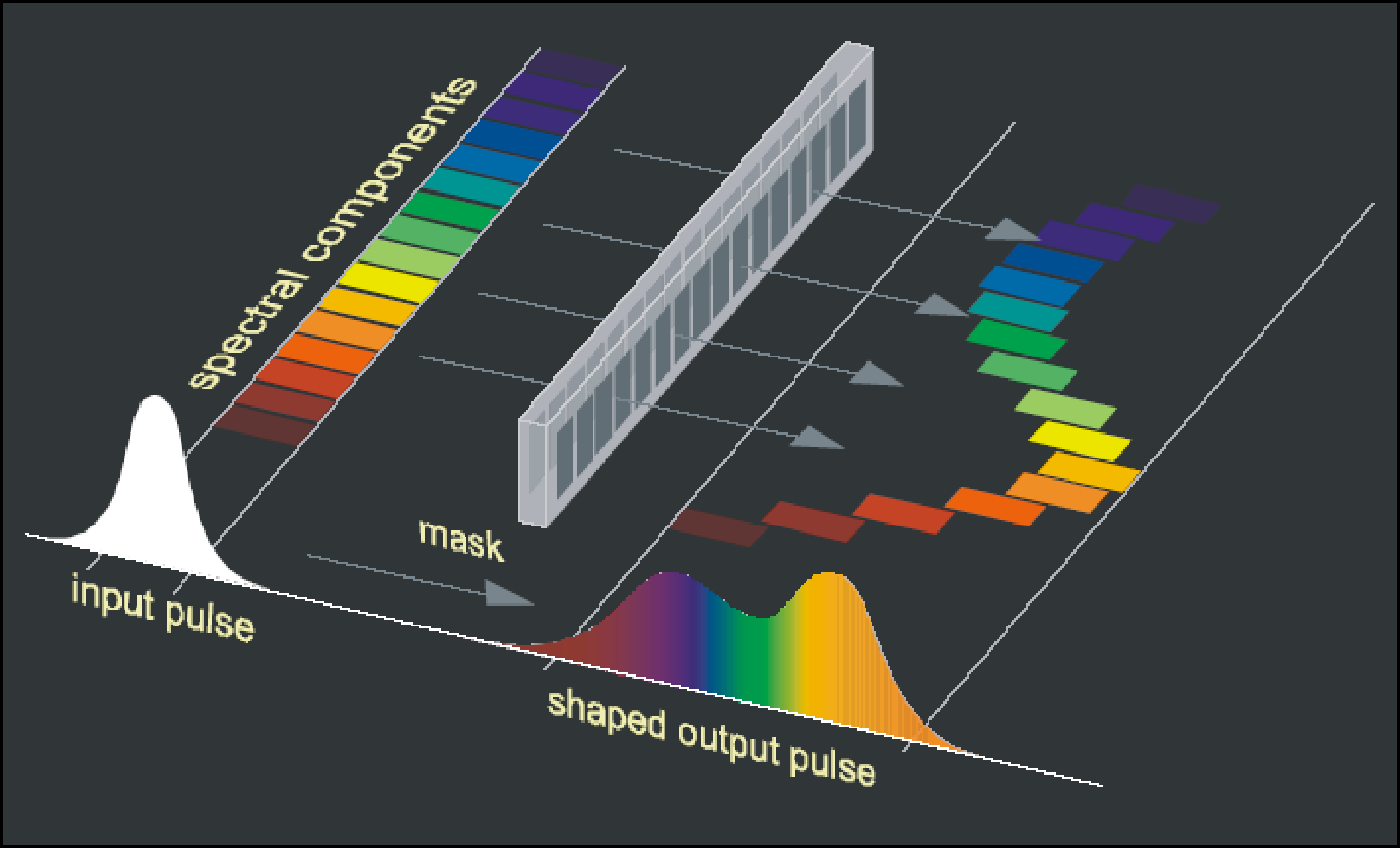
The first lens maps angle (hence wavelength) to position.

The second lens and grating undo the spatio-temporal distortions.

The trick is to place a mask in the Fourier transform plane.

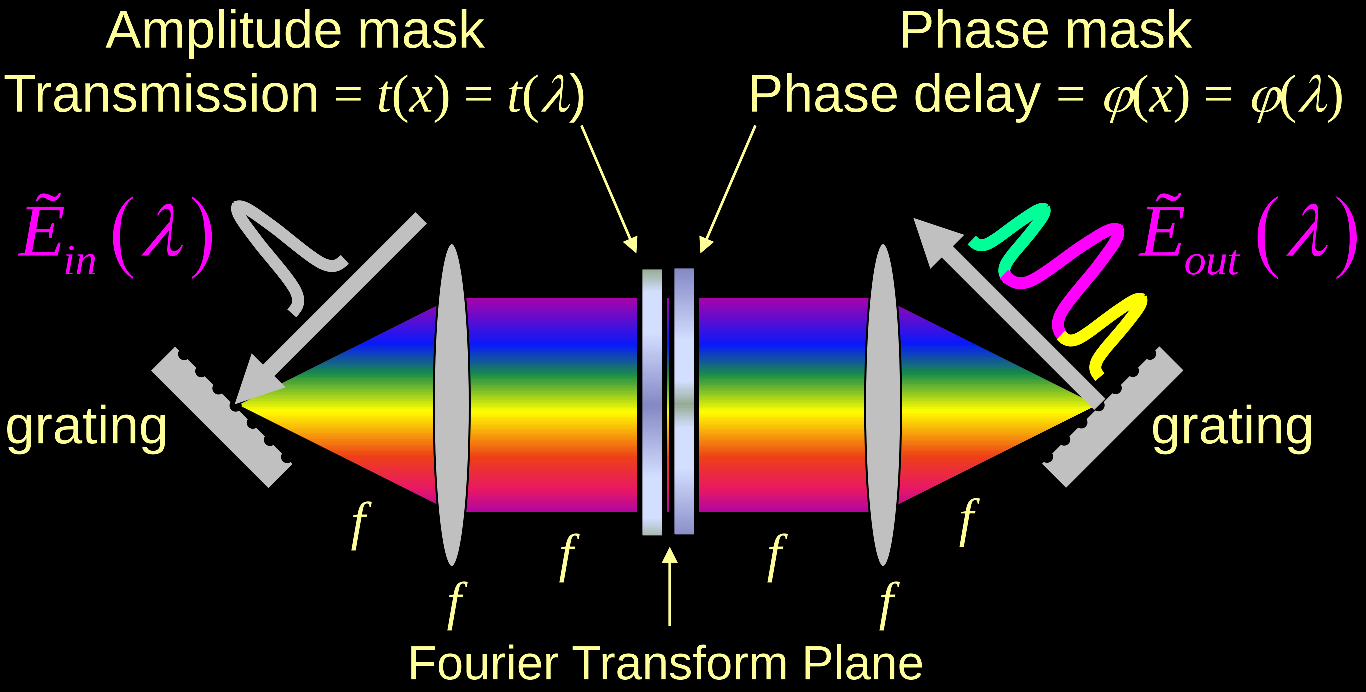
John Heritage, UC Davis
Andrew Weiner, Purdue

A phase mask selectively delays colors.



An amplitude mask shapes the spectral intensity.

The Fourier-synthesis pulse-shaper



$$\boxed{H(\lambda) = t(\lambda)\exp[i\varphi(\lambda)]}$$

We can control both the amplitude and phase of the pulse.

The two masks or “spatial light modulators” together can yield any desired pulse.

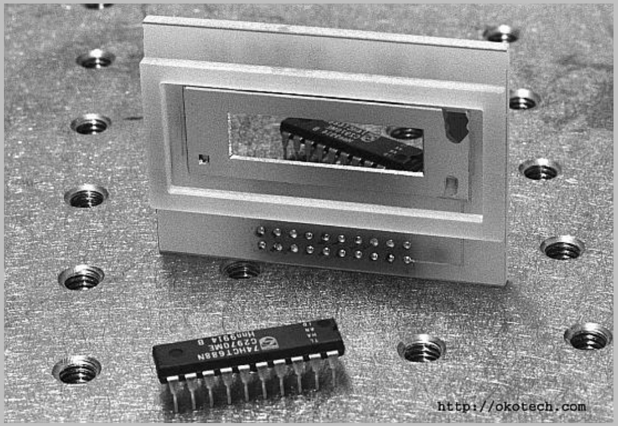
Some common spatial light modulators.

Early pulse shapers used **masks created using lithographic** techniques and that couldn't be modified once created.

More recent shapers use **spatial light modulators**, which can be programmed on the fly.

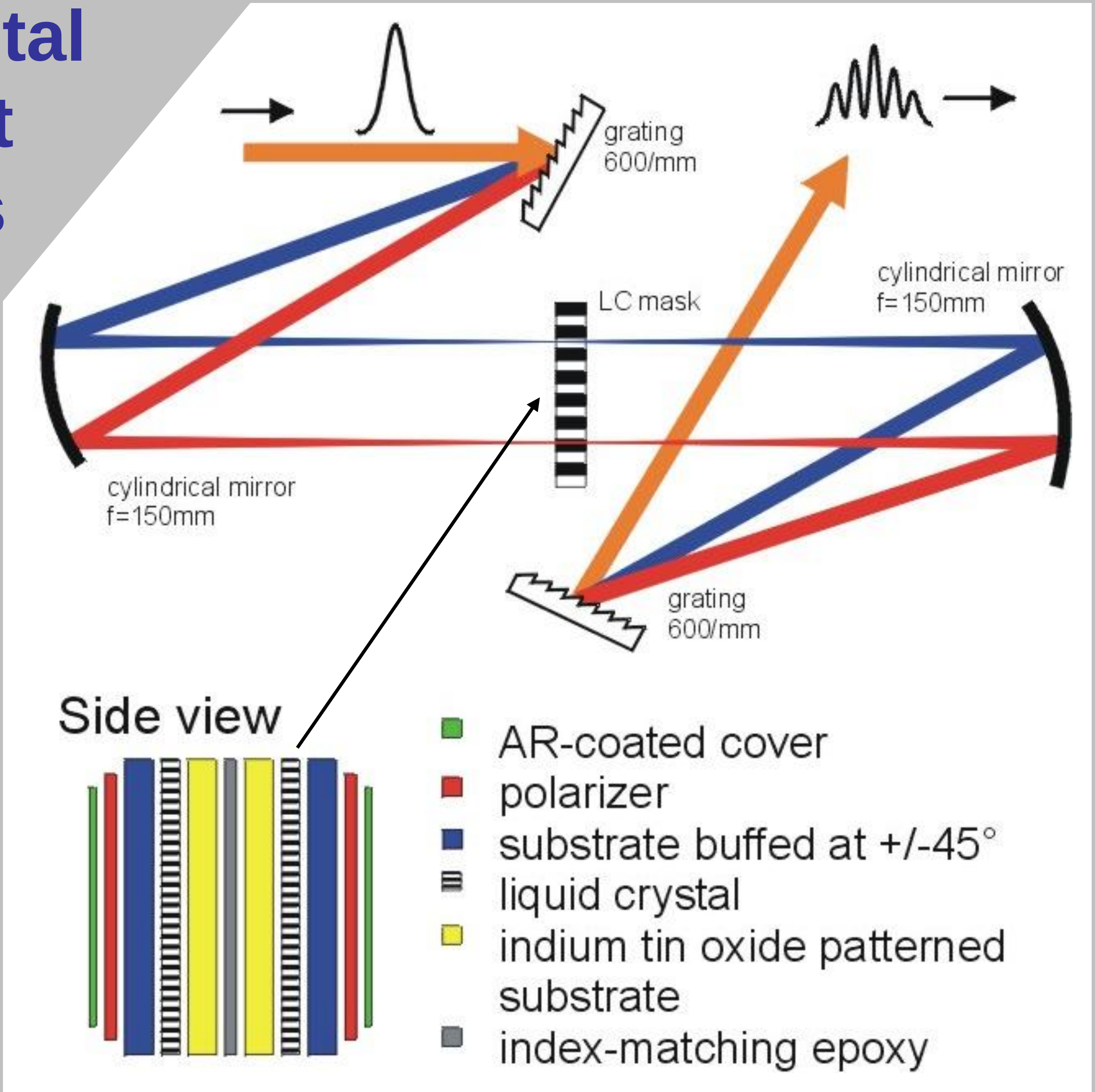
Types of spatial light modulators

- Liquid crystal arrays
- Acousto-optic modulators
- Deformable mirrors →

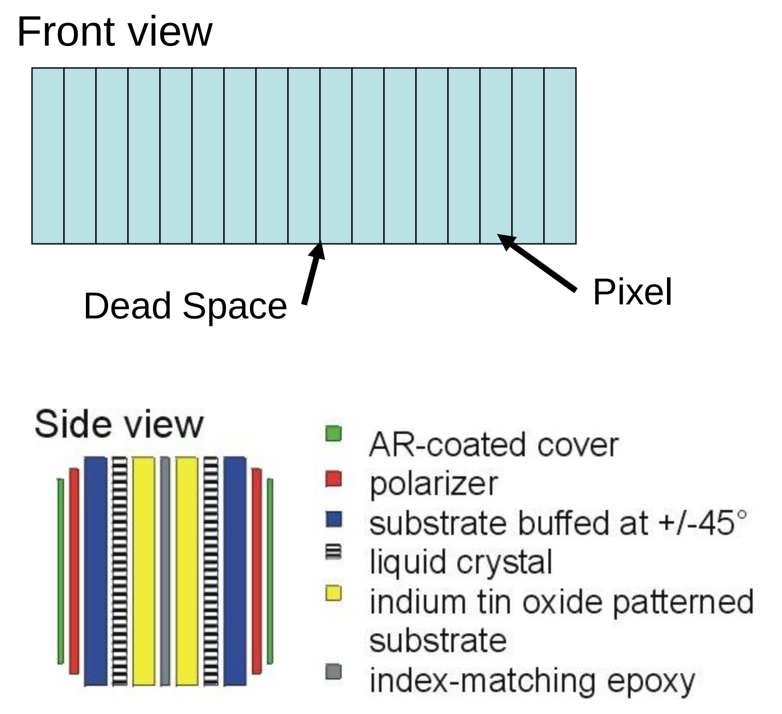


Liquid-crystal spatial light modulators

Liquid crystals orient along a an applied dc E-field. They yield a phase delay (or birefringence) that depends on an applied voltage. They can yield both phase and amplitude masks.



Liquid crystal arrays



Liquid crystal modulators (LCMs) consist of two liquid crystal arrays at 90° to each other and at 45° to the incoming light.

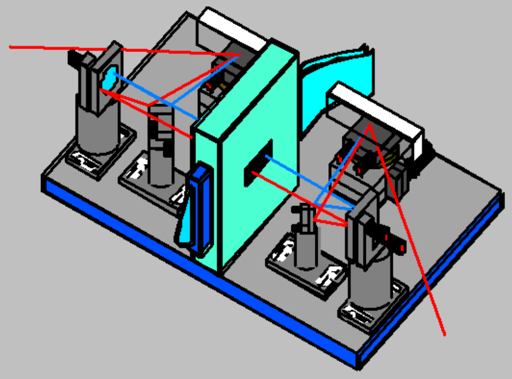
The first array rotates the polarization of the light in one direction and the second in the opposite direction.

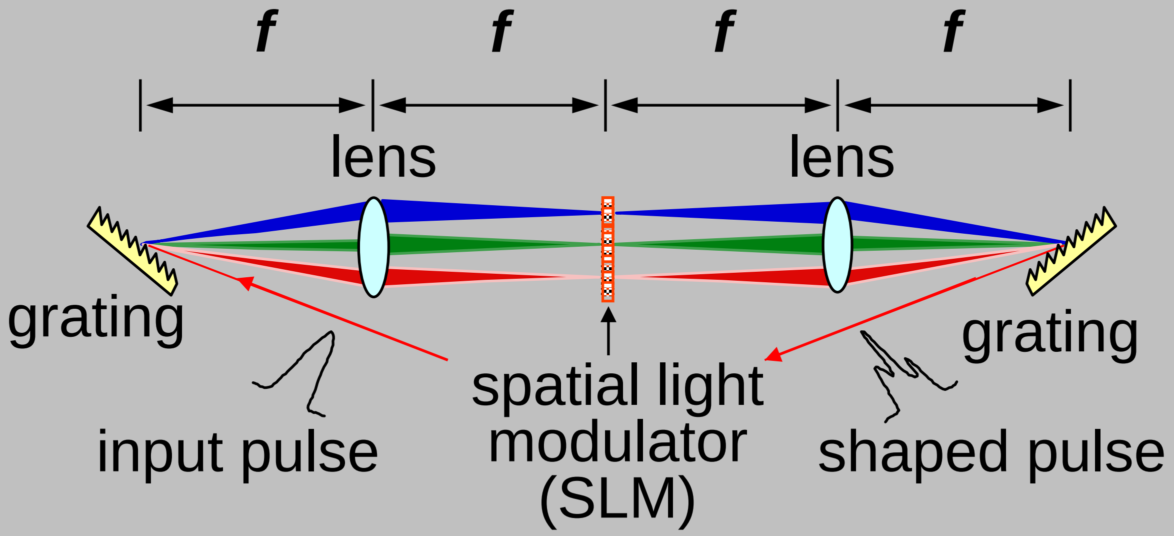
Rotating each the same amount (in opposite directions) yields a phase only modulation.

Rotating one more than the other yields an amplitude and phase modulation of the light.

The pixels in LCMs limit the resolution of the modulation. The finite width covers a range of wavelengths, reducing the fidelity of the shaping. The dead spaces (gaps between electrodes) also add artifacts to the pulse train.

Spatial-light-modulator pulse shaper: details





f *f* *f* *f*

lens

lens

grating

grating

input pulse

spatial light modulator (SLM)

shaped pulse

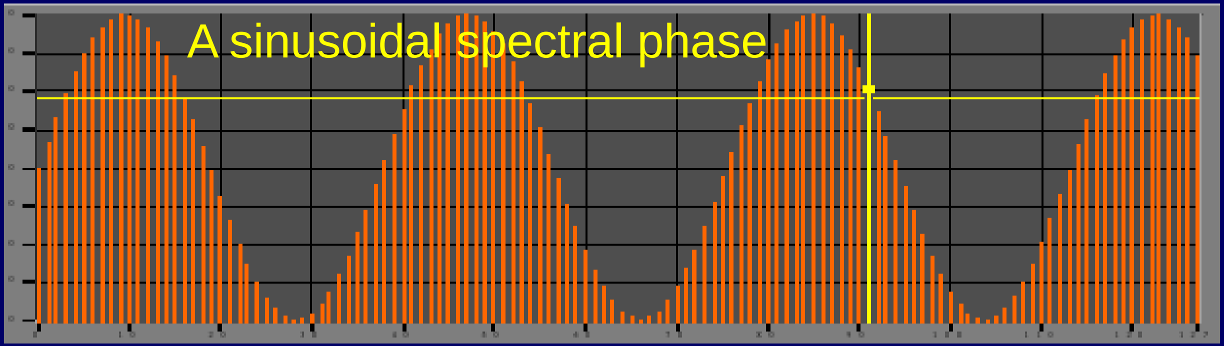
Parameters

SLM: 128 pixels (pixel width: 97 μm, pixel gap 3 μm)
Groove interval of the grating d^{-1}=651 lines/mm,
Input angle: 6.5 deg (100 nm bandwidth)
Focal length of the achromatic lens f = 145 mm

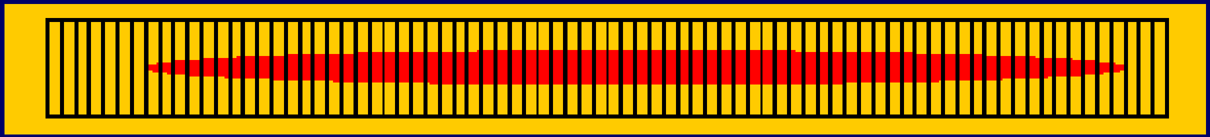
Takasumi Tanabe,
Kimihisa Ohno,
Tatsuyoshi Okamoto,
Fumihiko Kannari

[1] A.M.Weiner *et. al.*, IEEE J. Quantum Electron., **28** (1992) 908.
[2] K. Takasago *et. al.*, IEEE J. Select. Topics in Quantum Electron., **4** (1998) 346.

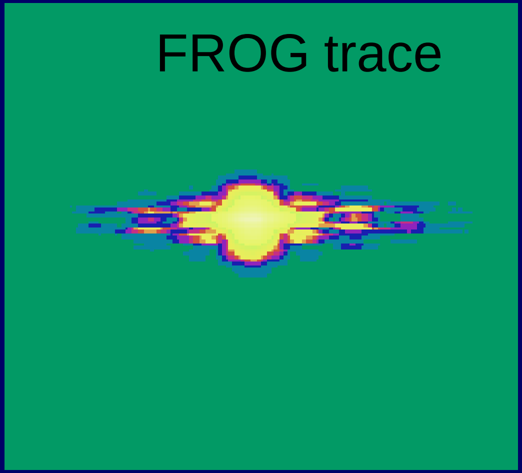
Spatial light modulator example

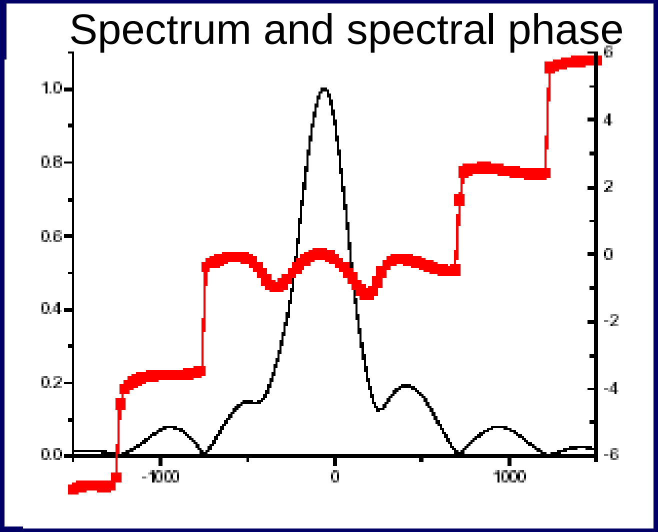


Voltage applied to SLM



Pulse illumination of SLM



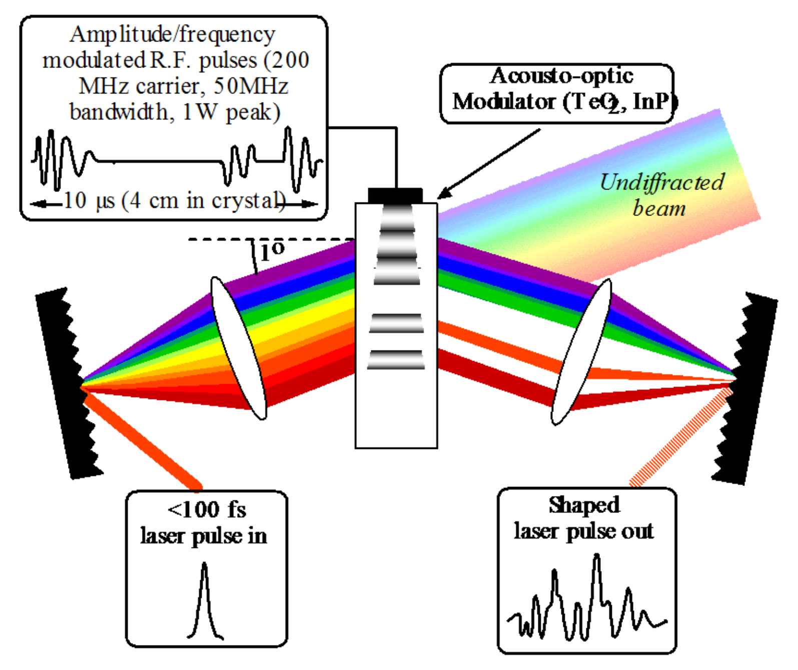


Resulting pulse shape

Omenetto and coworkers, LANL

Acousto-optic spatial light modulators

Acousto-optic modulators (AOM) offer a method of modulating the light.



AOMs offer both phase and amplitude modulation.

The strength of the sound wave is directly related to the intensity of the diffracted light.

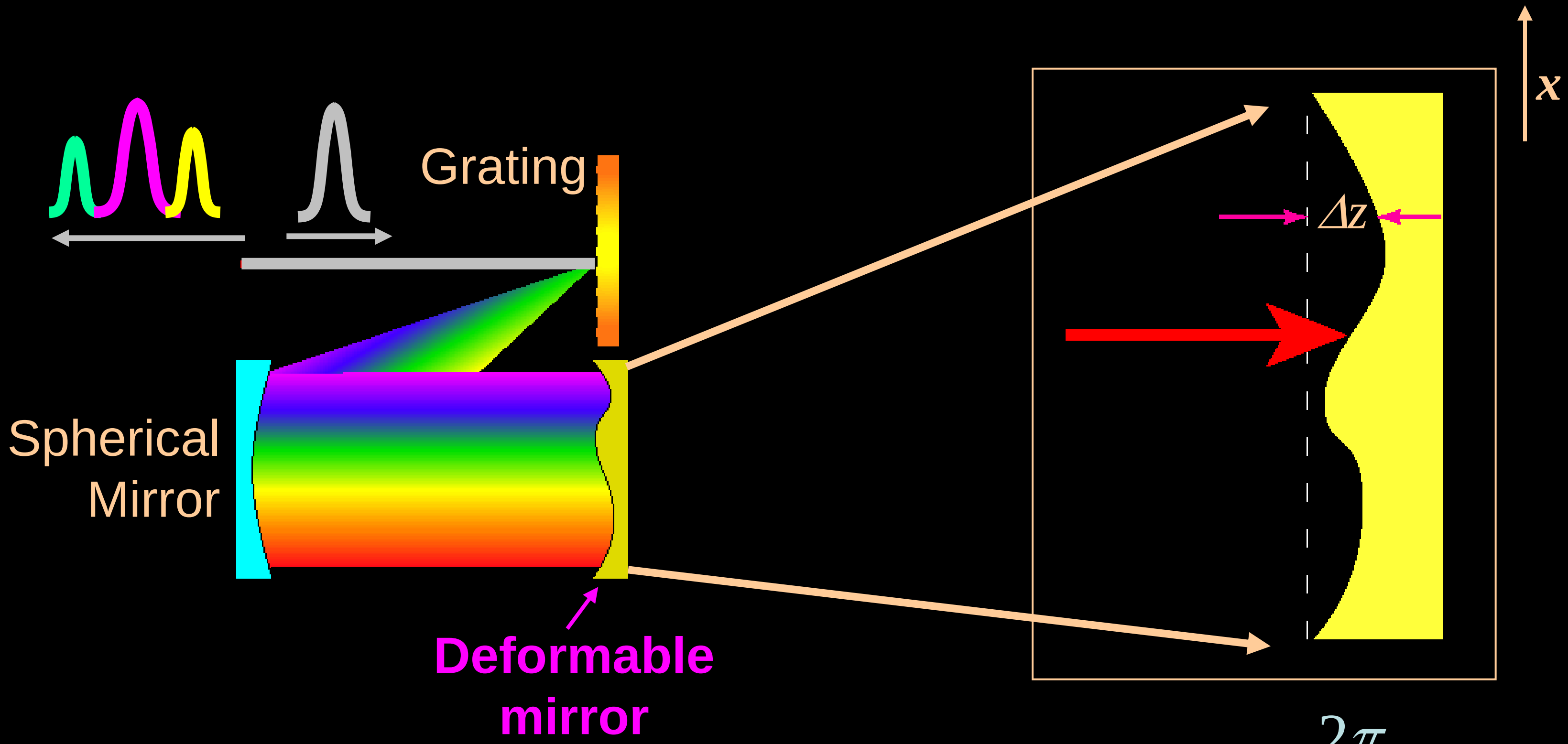
The phase of the sound wave is also written directly onto the diffracted light.

Warren Warren and coworkers, Princeton

AOMs have a very high number of effective “pixels,” the number of sound waves that fit across the aperture of the crystal.

AOM efficiency is less than other methods since it relies on the diffracted light.

Deformable-mirror pulse-shaper



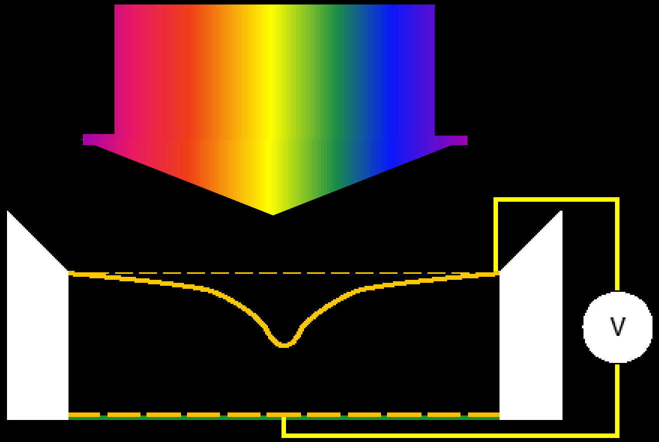
$$\Delta\varphi(x) = 2\,\frac{2\pi}{\lambda}\,\Delta z(x)$$

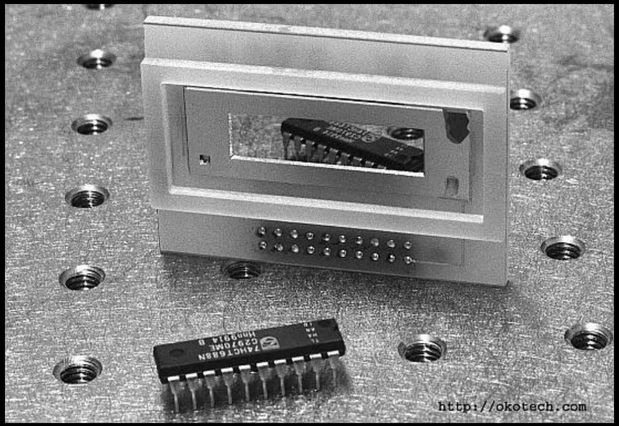
This modulates the phase but not the amplitude.

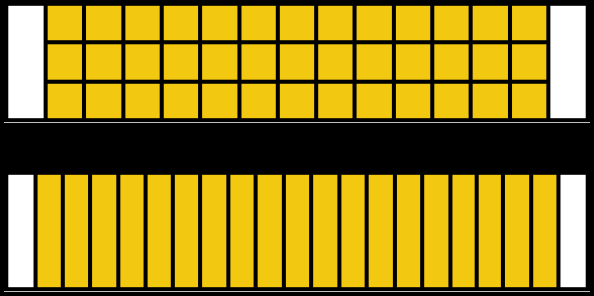
A. Efimov, and D. H. Reitze, Proc. SPIE **2701**, 190 (1996)
K. F. Wong, D. Yankelevich, K. C. Chu, J. P. Heritage, and A. Dienes, Opt. Lett. **18**, 558 (1993)

Deformable mirror pulse-shaper

- 600 nm Silicon Nitride Membrane
- Gold or Silver Coated
- 1 ms Response Time
- ~280 V Drive Voltage
- Computer Controlled
- 3x13 or 1x19 Actuator Layout







G.V. Vdovin and P.M. Sarro, ``Flexible mirror micromachined in silicon'', Applied Optics **34,** 2968-2972 (1995)

E. Zeek, et. Al., “Pulse compression using deformable mirrors”, Opt. Lett. **24**, 493-495 (1999)

Piezo-actuated deformable mirror (PADRE)

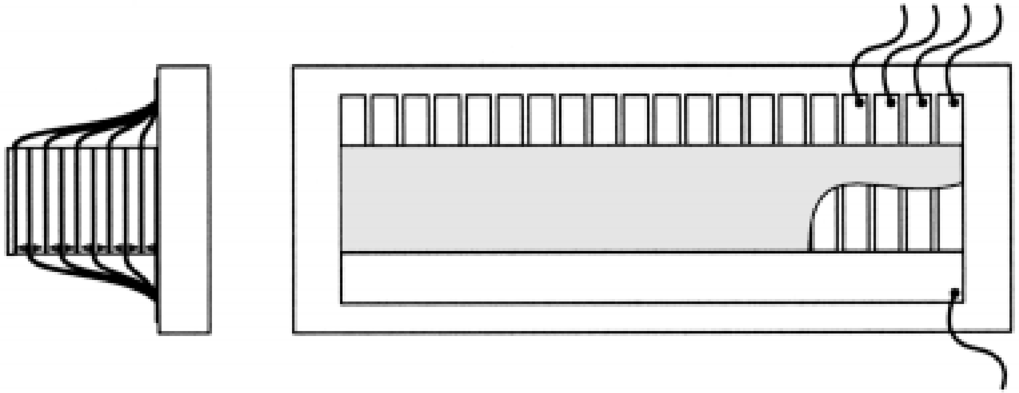
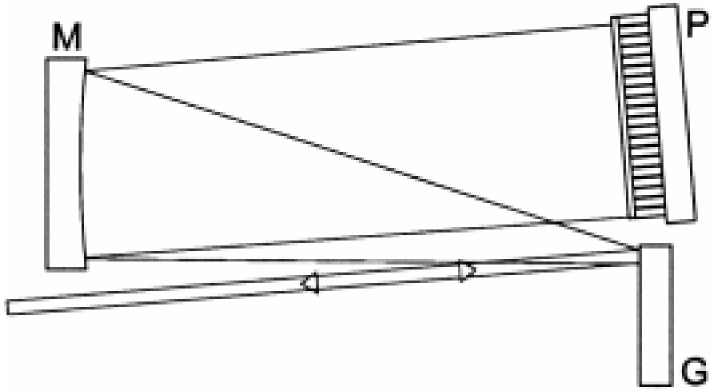
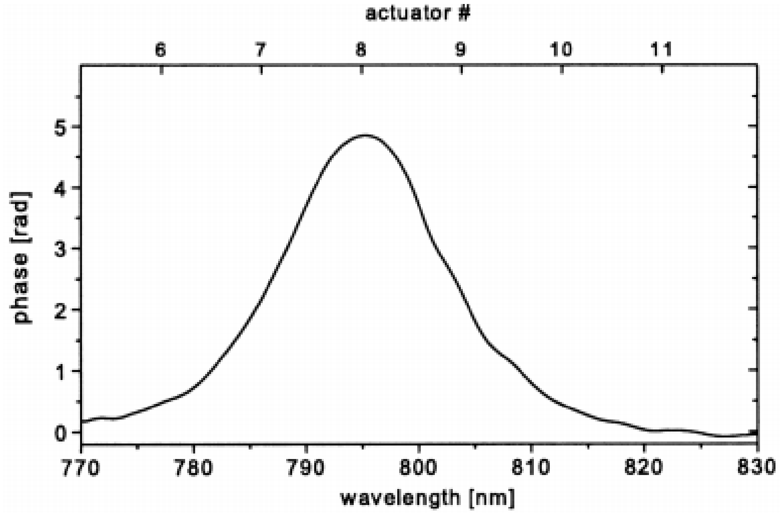
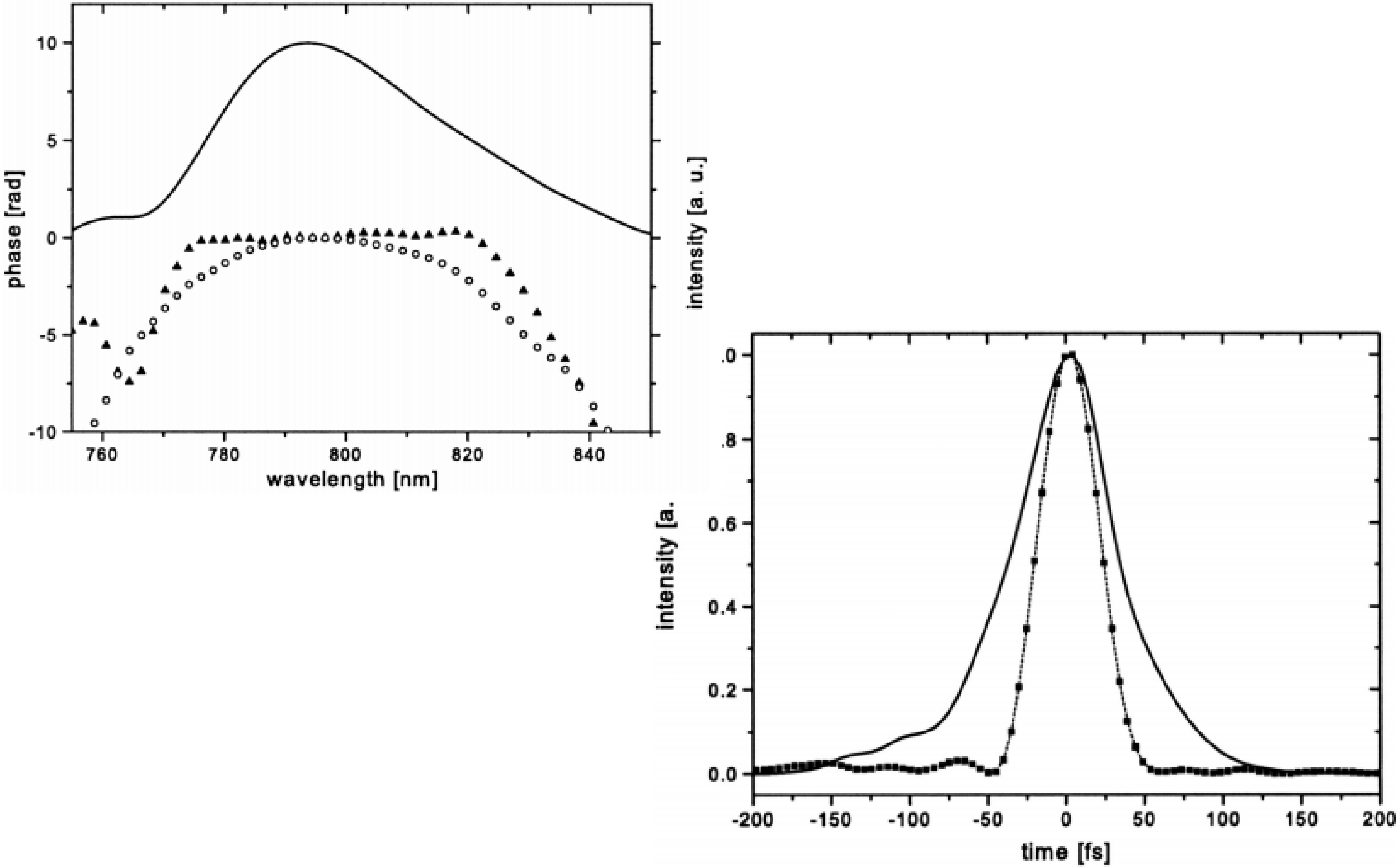


Fig. 1. Illustration of the PADRE. The device consists of a block of glass upon which 20 stacks of piezo elements are mounted in a row. Each stack consists of 12 layers. A 0.5-mm-thick plate of gold-coated glass is attached onto the top.



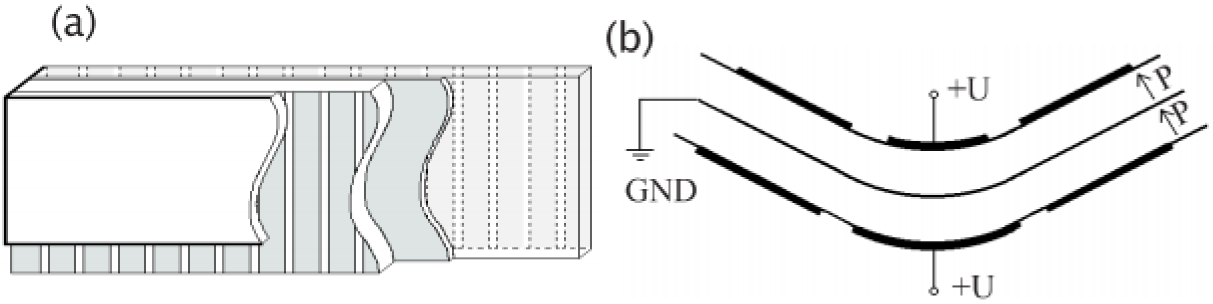


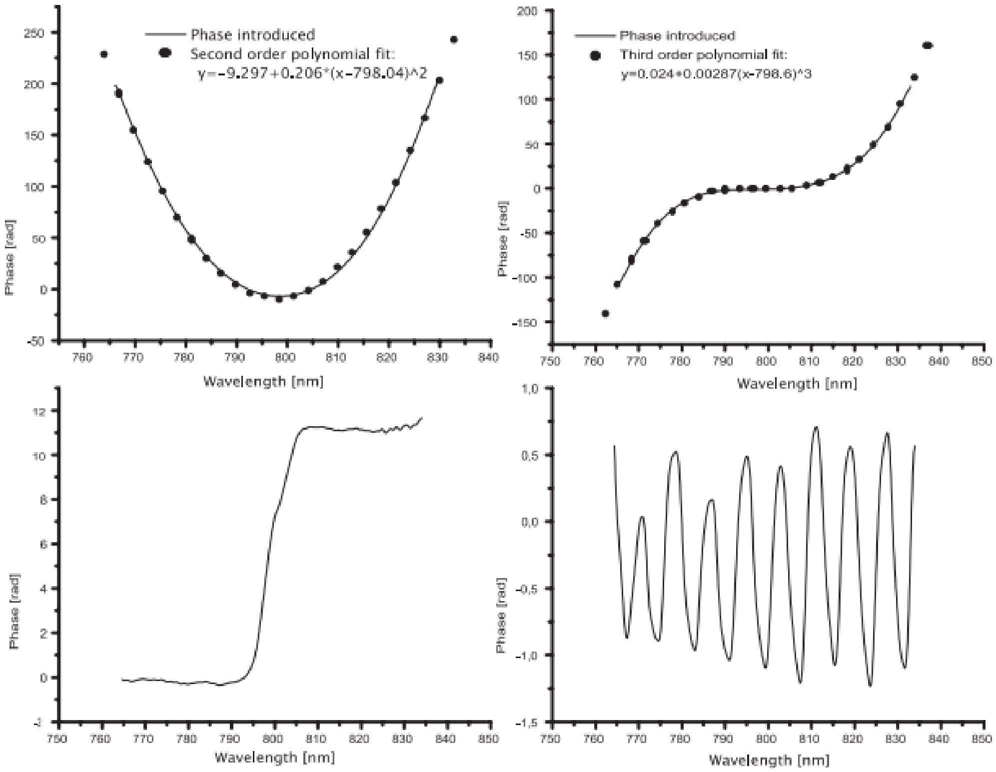
Piezo-actuated deformable mirror (PADRE)



C. Radzewicz, P. Wasylczyk, W. Wasilewski, J. S. Krasiński, Opt. Lett. 29, 177 (2004)

Bimorph deformable mirror





Bimorph deformable mirror

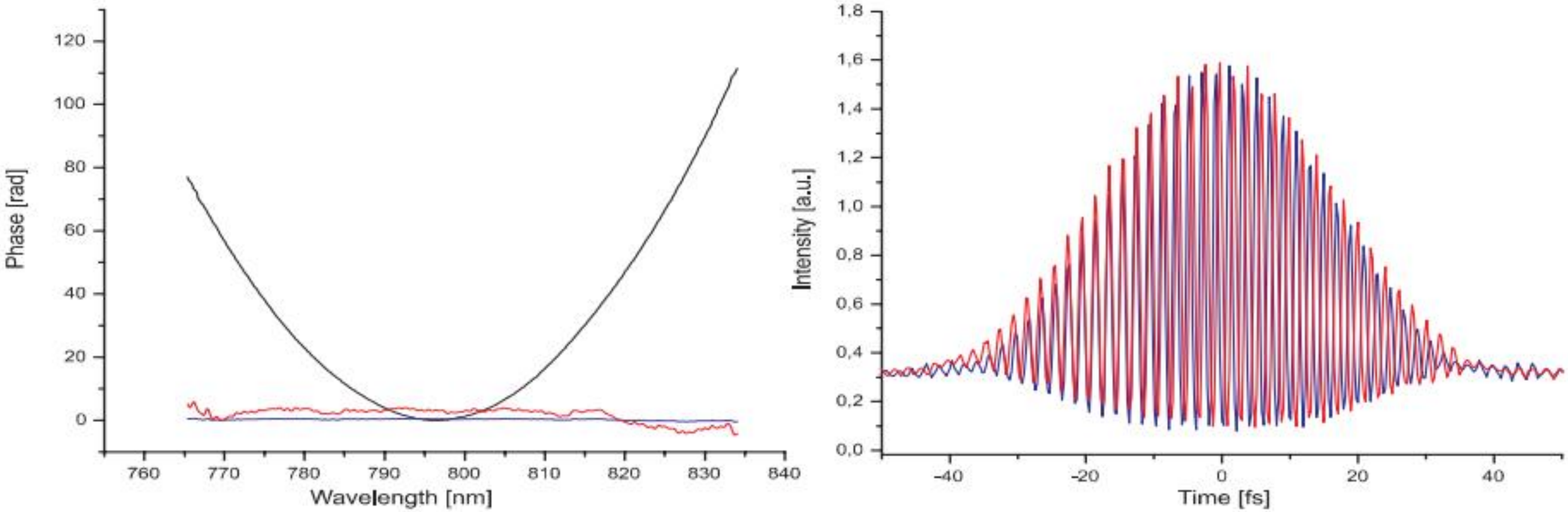


Fig. 4. (a) Spectral phase introduced by SF11 glass (black), the phase after compression (blue) and the phase after compression enlarged 10 (red). (b) Autocorrelation traces: blue – laser pulse, red – pulse after propagation through 10 cm of SF11 glass and compression.

P. Wnuk, C. Radzewicz, J. Krasiński, Opt. Express **13**, 4154 (2005)

Advantages and disadvantages of the various types of spatial light modulators

Liquid-Crystal Arrays

- Phase and amplitude modulation
- Pixellated with dead spaces
- Efficient

Acousto-Optic Modulators

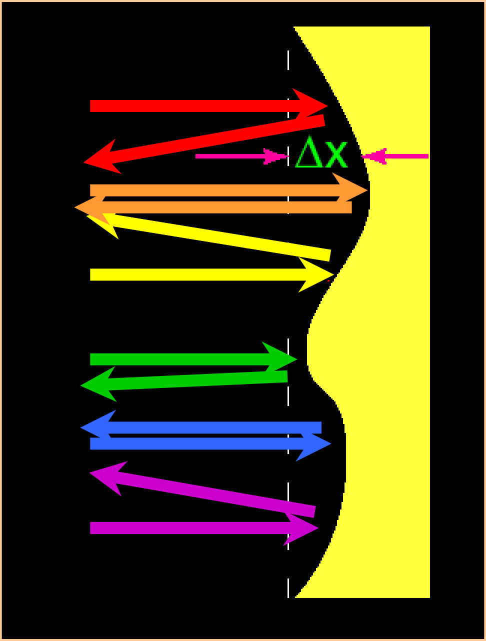
- Phase and amplitude modulation
- No dead spaces
- Small pixels
- Inefficient

Deformable Mirrors

- Phase-only modulation
- No dead spaces
- Large pixels
- Efficient

A **disadvantage** of all types of spatial light modulators

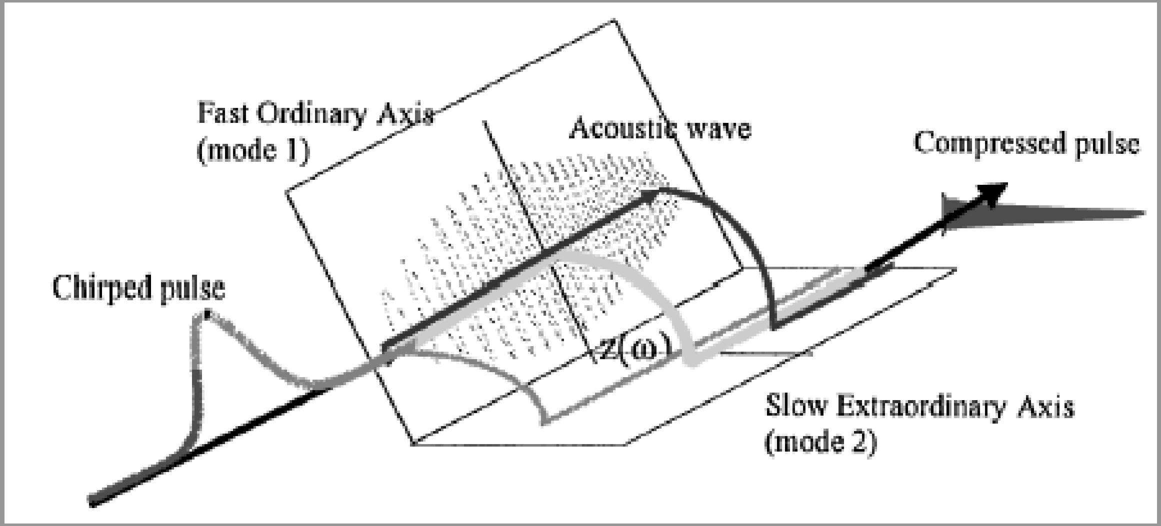
All spatial-light-modulator pulse-shapers induce spatio-temporal distortions in the pulse, which are proportional to the magnitude of the shaping.



Acousto-optic pulse-shaping

different from the
acousto-optic SLM!

This method works without the zero dispersion stretcher and hence without spatio-temporal pulse distortions.

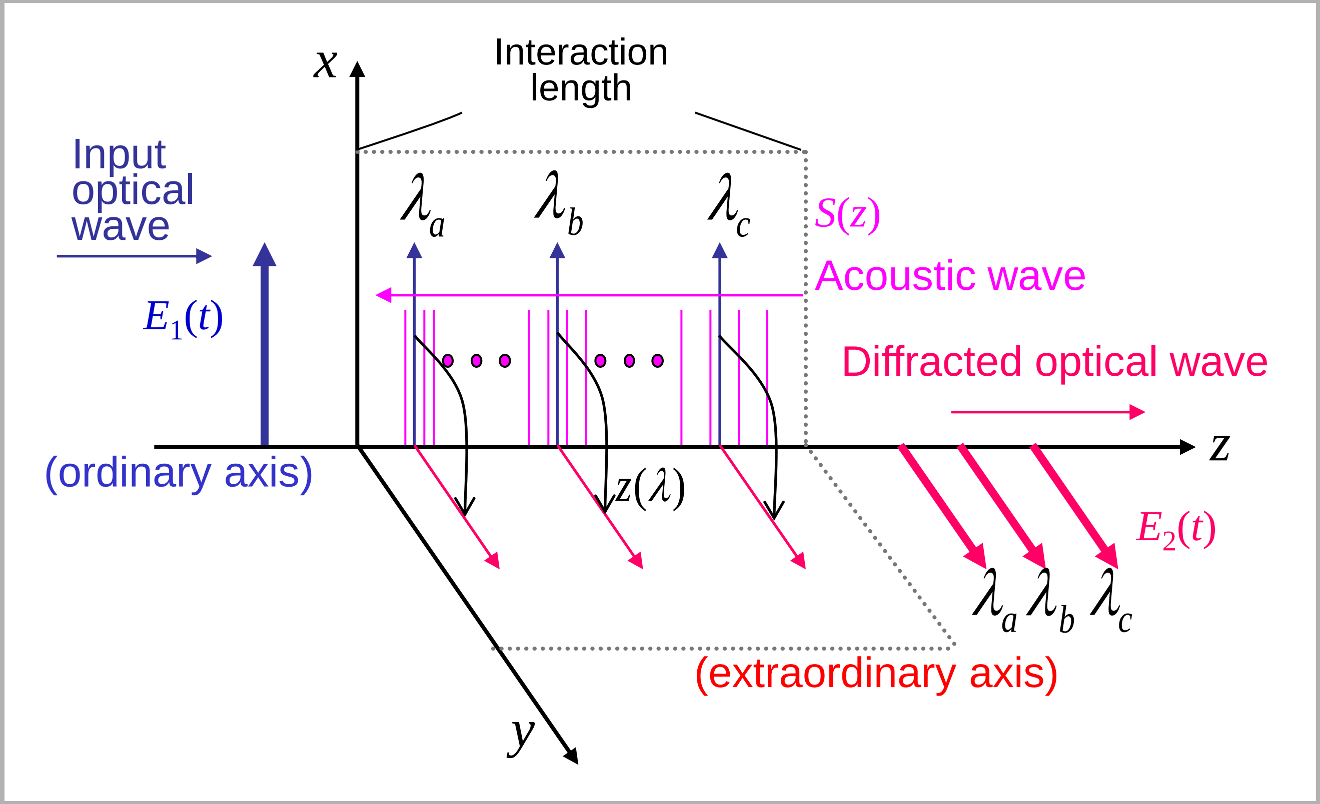


It launches an acoustic wave *along* the beam in a birefringent crystal.

The input polarization (say Ordinary, mode 1) is diffracted (coupled) to the other (Extraordinary, mode 2) by the sound wave. The frequency that is coupled depends on the acoustic-wave frequency. Its relative delay at the crystal exit depends on the relative group velocities of the two polarizations (O and E).

Acousto-optic pulse shaping: theory

The extra phase delay seen by each wavelength depends on how far into the crystal the acoustic wave takes on that wavelength and the ordinary and extraordinary refractive indices.

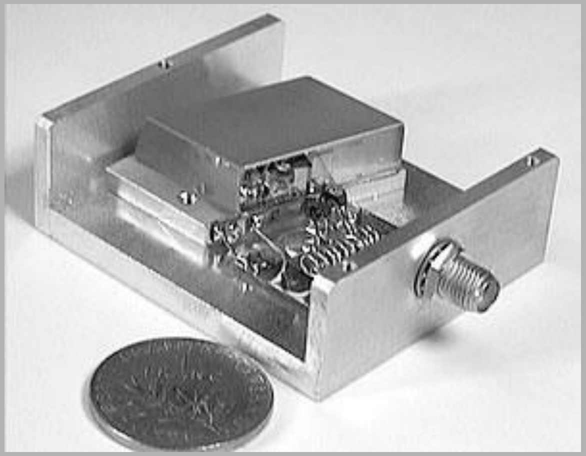


The strength of the acoustic wave at each wavelength determines the amplitude of the output wave at that wavelength.

$$\varphi(\lambda) = \{n_o(\lambda)z(\lambda) + n_e(\lambda)[L - z(\lambda)]\}\frac{2\pi}{\lambda}$$

Acousto-optic pulse-shaping: details

Acousto-optic pulse shaping yields intensity-and-phase shaping, it induces no spatio-temporal pulse distortions, and it is available commercially.



Commercial device: the “Dazzler”

Parameters

RF signal:
  center frequency:52.5 MHz, Bandwidth > 10 MHz
  dynamic range > 50 dB
Crystal: TeO_2 Crystal length: 25 mm (corresponds to 3 ps)
Operation frequency: 1 kHz
Complex programming (control data 4096 × 16 bits)

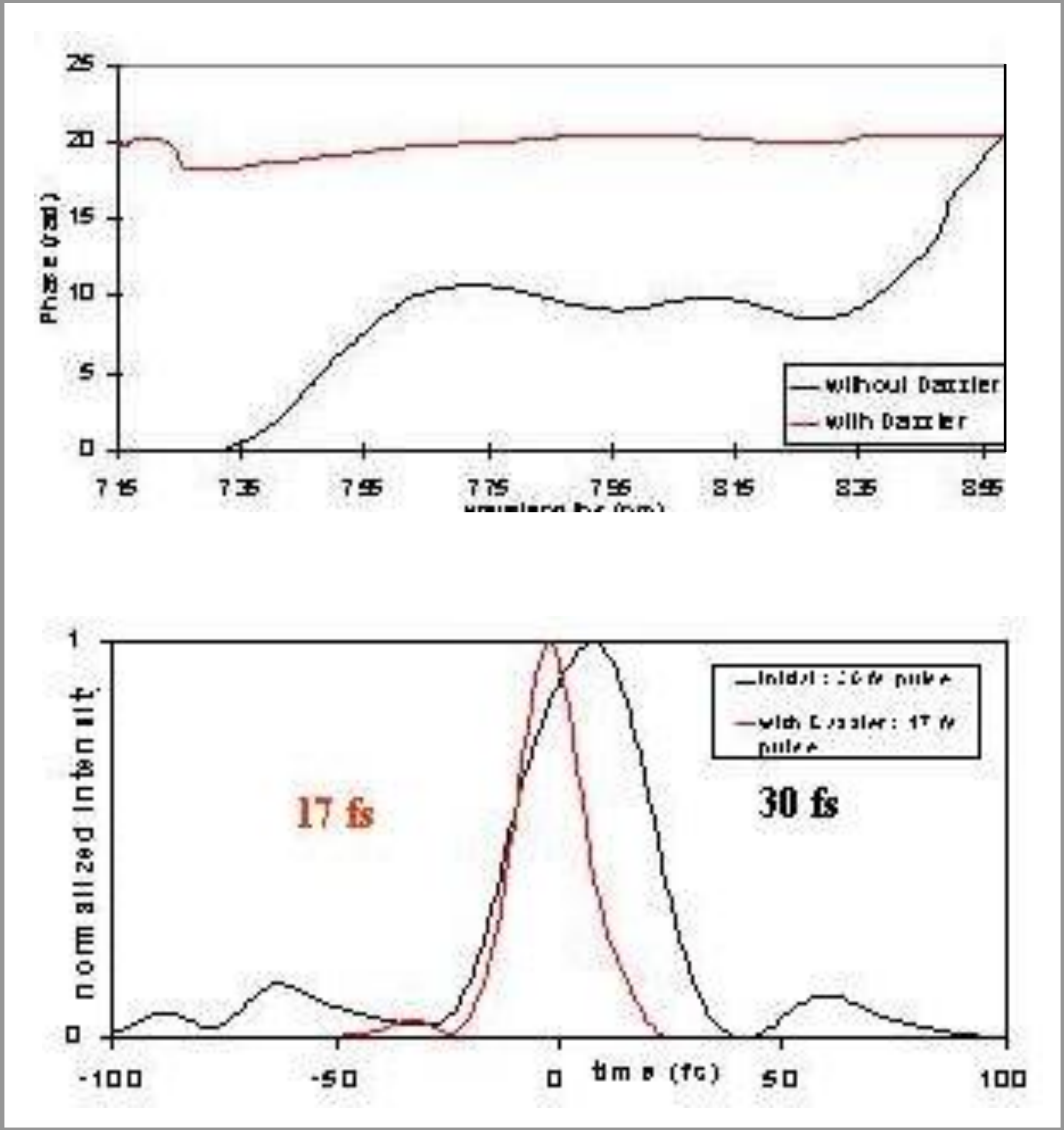
Takasumi Tanabe,
Kimihisa Ohno,
Tatsuyoshi Okamoto,
Fumihiko Kannari

[1] F. Verluise *et. al.*, Opt. Lett. **8** (2000) 575.
[2] K. Ohno *et. al.*, J. Opt. Soc. Am. B, **19** (2002) in press

Results using the Dazzler

Compensating the phase of an ultrashort pulse

The resulting pulse length is reduced from 30 fs to 17 fs.



Phase-only pulse shaping is more efficient. But can it achieve the desired pulse shape?

Can we generate a given pulse with only a phase mask?

Mostly.

But calculating a phase-only mask is difficult.

Generally we're given a target wave-form.

Direct calculation of $H(\omega)$ requires a phase **and amplitude** mask.

$$H(\omega) = \frac{\tilde{E}_{out}(\omega)}{\tilde{E}_{in}(\omega)}$$

We must calculate the best possible phase-only mask.

There now exist a whole class of optimization algorithms that specialize in such difficult (or impossible) problems.

The most common are Evolutionary (also called "Genetic") Algorithms

Evolutionary algorithms

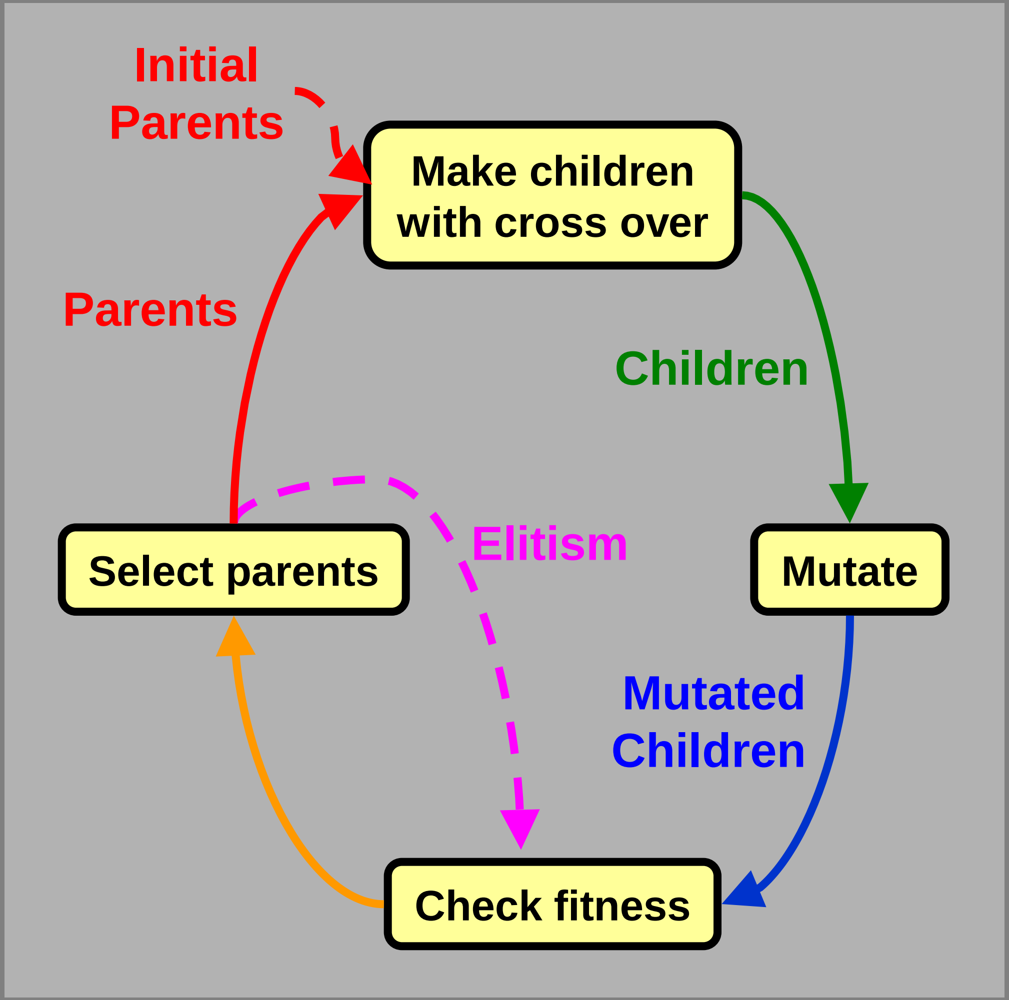
Evolutionary algorithms base their optimization on a simple axiom:

Survival of the fittest.

Evolutionary algorithms:

- don’t require a carefully chosen initial guess and hence
- provide a simple and very robust optimization method.

Evolutionary algorithms perform a pseudo random search.



Start with a set of parents (initially random).

Make a set of children. Using crossover to combine parts of parents.

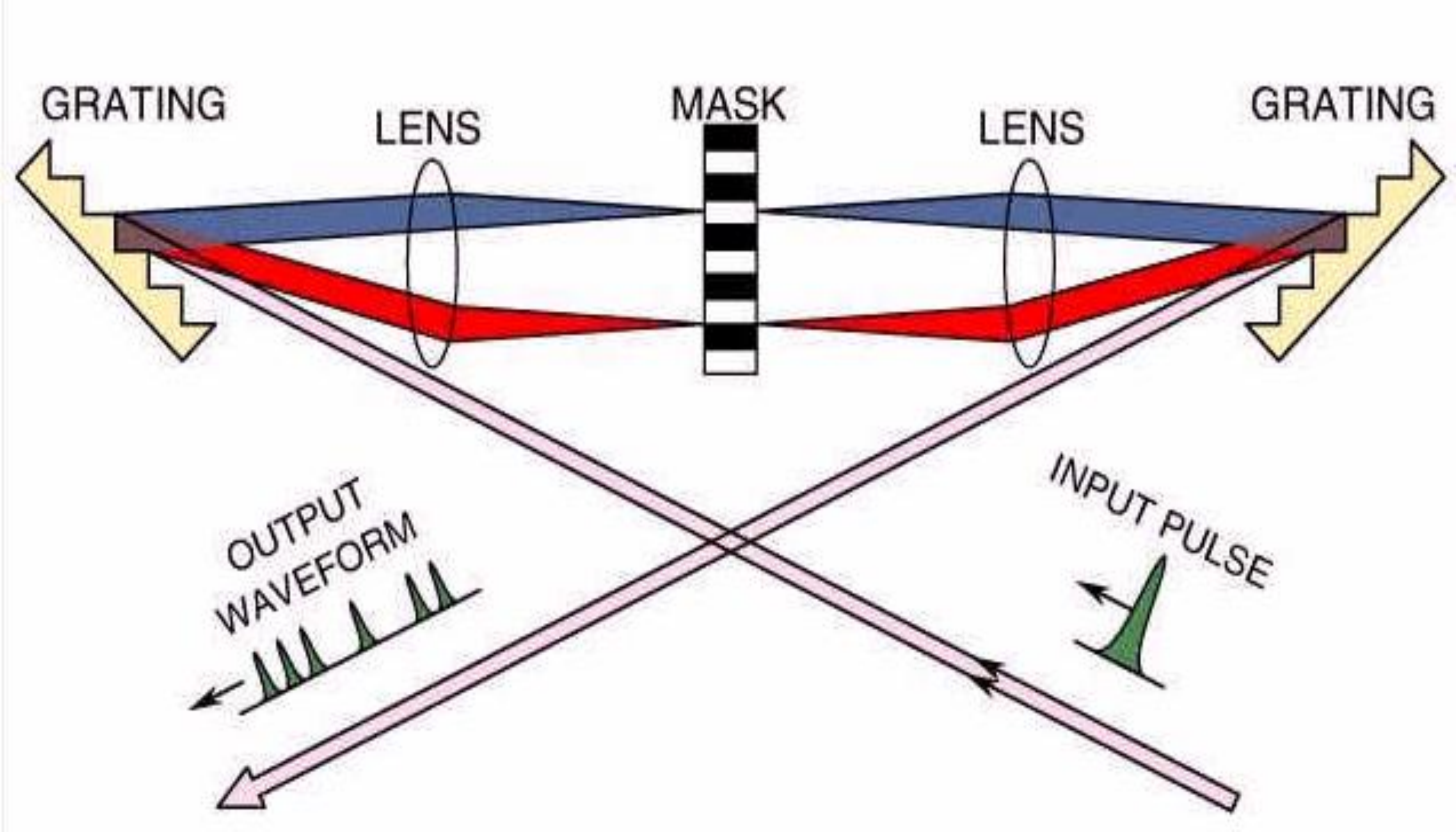
Add random mutations.

Evaluate the fitness of the individuals. If we keep the parents from the last generation, it’s called elitism.

Select the parents for the next generation.

Pulse-shaping for telecommunications

The goal is to create multiple pulses with variable separations.



A shaped pulse for telecommunications