Chirped Pulse Amplification

- Short pulse oscillator
- Dispersive delay line
- Solid state amplifiers
- Pulse compressor
Higher laser peak powers (laser intensity)

- **reduce pulse duration**
- **increase pulse energy content**

nonlinear processes important

To go past this limit needed gain media with
(1) available bandwidth sufficient to support amplification
(2) capability of high-energy storage

\[ F_{sat} = \frac{\hbar \omega}{\sigma_{21}} \]

Efficient energy extraction → input laser fluence to amplifier ~ \( F_{sat} \)

Media have small \( \sigma_{21} \) → large \( F_{sat} \)

solid state media have saturation fluences ~ 20J/cm²
→ for 100fs pulse intensities reach 10 to 200 TW/cm²

Solution:

**Chirped Pulse Amplification** (mid 80s)
Pulse energy vs. Repetition rate

Rep rate (pps)

Pulse energy (J)

Oscillator
Cavity-dumped oscillator
Regen
Regen + multipass
Regen + multipass
RegA
1 W average power

1 W average power
What are the goals in ultrashort pulse amplification?

**Maximum intensity on target**

\[ I_{\text{peak}} = \frac{E}{A \Delta t} \]

- Increase the energy \((E)\),
- Decrease the duration \((\Delta t)\),
- Decrease the area of the focus \((A)\)

Needed to start the experiment

**Maximum average power at the detector**

\[ P_{\text{ave}} = E \cdot r \]

- Signal is proportional to the number of photons on the detector per integration time.
- Needed to get useful results
Issues in Ultrafast Amplification and Their Solutions

Pulse length discrepancies: Multi-pass amplifiers and regenerative amplifiers ("Regens").

Damage: Chirped-Pulse Amplification (CPA)

Gain saturation: Frantz-Nodvick Equation

Gain narrowing: birefringent filters

Thermal effects: cold and wavefront correction

Satellite pulses, Contrast, and Amplified Spontaneous Emission: Pockels’ cells

Commercial systems: lots of money!
Before we consider amplification, recall that the intracavity pulse energy is ~50 times the output pulse energy.

What if we instead used two high reflectors, let the pulse energy build up, and then switch out the pulse. This is the opposite of Q-switching: it involves switching from minimum to maximum loss, and it’s called “Cavity Dumping.”
Cavity dumping: the Pockels cell

A Pockels cell is a device that can switch a pulse (in and) out of a resonator. It’s used in Q-switches and cavity dumpers.

A voltage (a few kV) can turn a crystal into a half- or quarter-wave plate.

If $V = 0$, the pulse polarization doesn’t change.

If $V = V_p$, the pulse polarization switches to its orthogonal state.

Abruptly switching a Pockels cell allows us to extract a pulse from a cavity. This allows us to achieve $\sim 100$ times the pulse energy at $1/100$ the repetition rate (i.e., 100 nJ at 1 MHz).
Amplification of Laser Pulses

Very simply, a powerful laser pulse at one color pumps an amplifier medium, creating an inversion, which amplifies another pulse.

Nanosecond-pulse laser amplifiers pumped by other ns lasers are commonplace.
What’s different about amplifying ultrashort laser pulses?

The first issue is that the ultrashort pulse is so much shorter than the (ns or ms) pump pulse that supplies the energy for amplification.

So should the ultrashort pulse arrive early or late?

Early:

- Pump energy arrives too late and is wasted.

Late:

- Energy decays and is wasted.

In both cases, pump pulse energy is wasted and amplification is poor.
So we need many passes.

All ultrashort-pulse amplifiers are multi-pass.

The ultrashort pulse returns many times to eventually extract most of the energy.

This approach achieves much greater efficiency.
Two Main Amplification Methods

**Multi-pass amplifier**
- Input
- Gain
- Pump
- Output

**Regenerative amplifier**
- Input/output
- Polarizer
- Pockels cell
- Gain
- Pump
A Multi-Pass Amplifier

A Pockels cell (PC) and a pair of polarizers are used to inject a single pulse into the amplifier.
Regenerative Amplifier Geometries

Two regens.

The design in (a) is often used for kHz-repetition-rate amplifiers and the lower (b) at a 10-20-Hz repetition rate. The lower design has a larger spot size in the Ti:sapphire rod.

The Ti:sapphire rod is usually ~20-mm long and doped for 90% absorption.
Pulse intensities inside an amplifier can become so high that damage (or at least small-scale self-focusing) occurs.

Solution:

Expand the beam and use large amplifier media.

Okay, we did that. But that’s still not enough.

Solution:

Expand the pulse in time, too.
Chirped Pulse Amplification

Chirped-pulse amplification involves stretching the pulse, amplifying it, and then recompressing it later.

We can stretch the pulse by a factor of 10,000, amplify it, and then recompress it!

CPA is THE big development.

G. Mourou and coworkers 1983
stretcher-compressor system is the key

First implementation

stretch with optical fiber (+ve GVD)
compressed by a pair of gratings (-ve GVD)

• 100x peak power
• problem stretcher - compressor were not perfectly matched
  (dispersions unbalanced)
• also pre-pulses and post-pulses

Solution →
Martinez grating “compressor”
which is the matched stretcher of
the Treacy compressor
Lawrence Livermore Labs Pulse Stretcher

This device stretches an 18-fs pulse to 600 ps—a factor of 30,000!

A ray trace of the various wavelengths in the stretcher:

Pulse stretcher characteristics:
- Input pulse width: 18 fs
- Output pulse duration: 600 ps
- Bandwidth passed: >105 nm
- Pulse energy out: ~0.5 nJ
CPA vs. Direct Amplification

CPA achieves the fluence of long pulses but at a shorter pulse length!
Regenerative Chirped-Pulse Amplification at \(~100\) kHz with a cw pump

A fs oscillator requires only \(~5\) W of green laser power. An Argon laser provides up to \(50\) W. Use the rest to pump an amplifier. Today, we use a intracavity-doubled Nd:YLF pump laser (\(~10\)W).

Microjoules at \(250\) kHz repetition rates!
Regenerative Chirped-Pulse Amplification with a kHz pulsed pump.

Wavelength: 800 nm
(Repetition rates of 1 to 50 kHz)
High Energy: <130 fs, >2 mJ at 1 kHz
Picosecond: ~80 ps, >0.7 mJ at 1 kHz
Short Pulse: <50 fs, >0.7 mJ at 1 kHz

Positive Light regen: the “Spitfire”
Pump laser for ultrafast amplifiers

15 mJ at a 10 kHz rep rate
(150W ave power!)

Coherent “Corona”

high power, Q-switched green laser in a compact and reliable diode-pumped package
# Average Power for High-Power Ti:Sapphire Regens

<table>
<thead>
<tr>
<th></th>
<th>Rep rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 kHz</td>
</tr>
<tr>
<td>Extracted energy</td>
<td>20 mJ</td>
</tr>
<tr>
<td>Average Power</td>
<td>20 W</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>3 mm</td>
</tr>
</tbody>
</table>

Pump power 100 W

These average powers are high. And this pump power is also. If you want sub-100fs pulses, however, the energies will be less.
CPA is the basis of thousands of systems.

It’s available commercially in numerous forms.

It works!

**But there are some issues, especially if you try to push for really high energies:**

- Gain saturation: gain vs. extraction efficiency
- Gain narrowing
- Thermal aberrations
- Contrast ratio
- Damage threshold *vs* extraction efficiency
Gaussian pulse shapes

\[ e(t) = A_0 e^{-\frac{t^2}{\tau^2}} e^{i\omega_0 t + \psi(t)} \]

\[ E(\omega) = \int_{-\infty}^{\infty} e(t) e^{-i\omega t} dt = A(\omega) e^{i\eta(\omega)} \]

Each element in the optical path, has a spectral response

\[ \psi(\omega) = \psi(\omega_0) + \psi'(\omega_0)(\omega - \omega_0) + \frac{1}{2} \psi''(\omega_0)(\omega - \omega_0)^2 + \frac{1}{6} \psi'''(\omega_0)(\omega - \omega_0)^3 \]

Group delay \hspace{1cm} Group velocity dispersion \hspace{1cm} Third order delay

A pulse through optical elements and laser materials is affected from the above individual contributions are determined by the refractive index (Sellmeir empirical forms)

\[ n(\lambda) \]
Laser materials

GVD
\[ \frac{d^2 \omega_{\nu}(\omega)}{d\omega^2} = \frac{\lambda^2 \epsilon}{2\pi c^2} \frac{d^2 n(\lambda)}{d\lambda^2} \]

TOD
\[ \frac{d^3 \omega_{\nu}(\omega)}{d\omega^3} = \frac{-\lambda^4 \epsilon}{4\pi^2 c^2} \left( 3 \frac{d^2 n(\lambda)}{d\lambda^2} + \frac{\lambda d^3 n(\lambda)}{d\lambda^3} \right) \]

FOD
\[ \frac{d^4 \omega_{\nu}(\omega)}{d\omega^4} = \frac{\lambda^5 \epsilon}{8\pi^3 c^3} \left( 12 \frac{d^2 P(\lambda)}{d\lambda^2} + 8\lambda \frac{d^3 P(\lambda)}{d\lambda^3} + \lambda^2 \frac{d^4 P(\lambda)}{d\lambda^4} \right) \]

Prism pair

GVD
\[ \frac{d^2 \eta_{\nu}(\omega)}{d\omega^2} = \frac{\lambda^2 \epsilon}{2\pi c^2} \frac{d^2 P(\lambda)}{d\lambda^2} \]

TOD
\[ \frac{d^3 \eta_{\nu}(\omega)}{d\omega^3} = \frac{-\lambda^4 \epsilon}{4\pi^2 c^2} \left( 3 \frac{d^2 P(\lambda)}{d\lambda^2} + \lambda \frac{d^3 P(\lambda)}{d\lambda^3} \right) \]

FOD
\[ \frac{d^4 \eta_{\nu}(\omega)}{d\omega^4} = \frac{\lambda^5 \epsilon}{8\pi^3 c^3} \left( 12 \frac{d^2 P(\lambda)}{d\lambda^2} + 8\lambda \frac{d^3 P(\lambda)}{d\lambda^3} + \lambda^2 \frac{d^4 P(\lambda)}{d\lambda^4} \right) \]
Grating pair

GVD
\[
\frac{d^2 \psi, (\omega)}{d \omega^2} = \frac{\lambda^2 \epsilon_0}{\pi c^2 d^2} \left( 1 - \left( \frac{\lambda}{d} - \sin \gamma \right)^2 \right)^{3/2}
\]

TOD
\[
\frac{d^2 \psi, (\omega)}{d \omega^2} = \frac{-6 \pi \lambda \cdot d^2 \psi, (\omega)}{c \cdot d \omega^2} \left( \frac{1 + (\lambda/d) \sin \gamma - \sin^2 \gamma}{1 - \left( \frac{\lambda}{d} - \sin \gamma \right)^2} \right)
\]

FOD
\[
\frac{d^2 \psi, (\omega)}{d \omega^3} = \frac{6 d^2}{c^2} \frac{d^2 \psi, (\omega)}{d \omega^2} = \frac{6 d^2}{c^2} \frac{d^2 \psi, (\omega)}{d \omega^2}
\]
\[
\left( \frac{8 \lambda^2}{d^2} + 20 - \frac{4 \lambda^2}{d^2} \cos \gamma + 16 \cos 2 \gamma - 4 \cos 4 \gamma + \frac{32 \lambda}{d} \sin \gamma + \frac{32 \lambda}{d} \sin 3 \gamma \right)
\]
\[
	imes \left( -\frac{\lambda}{d} + \frac{4d}{\lambda} + \frac{4d}{\lambda} \cos 2 \gamma + 32 \sin \gamma \right)^2 \left( -\frac{\lambda}{d} + \frac{4d}{\lambda} \cos 2 \gamma + 32 \sin \gamma \right)
\]

\[
\frac{d^2 \psi, (\omega)}{d \omega^3} \propto \lambda \cdot c \cdot \left( 1 + \frac{\lambda}{d} \sin \gamma - \sin^2 \gamma \right)
\]
\[
\frac{1}{c} \left( 1 - \left( \frac{\lambda}{d} - \sin \gamma \right)^3 \right)
\]
## 1cm thickness at 800nm

<table>
<thead>
<tr>
<th>Material</th>
<th>GVD  (d^2q/d\omega^2) [fs⁻²]</th>
<th>TOD  (d^3q/d\omega^3) [fs⁻³]</th>
<th>FOD  (d^4q/d\omega^4) [fs⁻⁴]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fused silica</td>
<td>361,626</td>
<td>274,979</td>
<td>-114,35</td>
</tr>
<tr>
<td>BK7</td>
<td>445,484</td>
<td>323,554</td>
<td>-98,718</td>
</tr>
<tr>
<td>SF18</td>
<td>1543,45</td>
<td>984,277</td>
<td>210,133</td>
</tr>
<tr>
<td>KDP</td>
<td>290,22</td>
<td>443,342</td>
<td>-376,178</td>
</tr>
<tr>
<td>Calcite</td>
<td>780,96</td>
<td>541,697</td>
<td>-118,24</td>
</tr>
<tr>
<td>Sapphire</td>
<td>581,179</td>
<td>421,756</td>
<td>-155,594</td>
</tr>
<tr>
<td>Sapphire @ Brewster angle</td>
<td>455,383</td>
<td>331,579</td>
<td>-114,912</td>
</tr>
<tr>
<td>Air</td>
<td>0,0217</td>
<td>0,0092</td>
<td>2,3x10⁻¹¹</td>
</tr>
<tr>
<td>Compressor 600 lp/mm, 13.89°</td>
<td>-3567,68</td>
<td>5101.21</td>
<td>-10226</td>
</tr>
<tr>
<td>prism pair SF18</td>
<td>-45,567</td>
<td>-181,516</td>
<td>-331,184</td>
</tr>
</tbody>
</table>
Stretching & Compressing

Pulse stretcher

a “zero-dispersion stretcher” but for $L < f$
dispersive stretcher up to 10,000!

chirped pulse [10 ps, 1 ns]

$\rightarrow$ damage threshold $5 \text{ J/cm}^2$ (5 GW/cm$^2$).
Stretching & Compressing

Pulse stretcher

\[ \tau_{\text{chip}} = \tau_{\text{int}} \sqrt{1 + \left( \frac{4 \ln 2 \cdot \text{GDD}}{\tau_{\text{m}}^2} \right)^2} \]

30 fs → 100 ps at 800 nm
GDD \sim 1.15 \times 10^6 \text{fs}^2

Grating pairs @ 1200 l/mm & Littrow 28.6°
need 29.8 cm for this GDD (net 2-pass)

Top: 2^{nd} grating away from lens f + \delta f, the axial ray travels a shorter path wrt the marginal ray
⇒ -ve dispersion

Bottom: 2^{nd} grating toward lens f – \delta f, the axial ray travels a longer path wrt the marginal ray
⇒ +ve dispersion
A 100fs pulse at 800nm broadens to 120ps by passing through a grating stretcher of 1200lp/mm at 40cm separation.

With no other material in the system, a matched compressor will recompress to the original pulse duration.

Through a typical regen amplifier, there is additional 44cm of sapphire, 22cm of silica, and 44cm of KDP.

To compensate their dispersion, the compressor gratings need an extra separation of 4.8cm, but this adds an extra $9 \times 10^4 \text{fs}^3$ TOD.

This can be balanced by the angles of the gratings (off Littrow angle) either in the stretcher or the compressor.

This balance is not possible with pulses of 20fs or less.
Assume a saturable gain medium and $J$ is the fluence (energy/area).

Assume all the pump energy is stored in the amplifier, but it will only have so much energy.

At low intensity, the gain is linear:

$$\frac{dJ}{dz} = g_0 J \quad \left( g_0 = \frac{J_{sto}}{J_{sat}} > 0 \right)$$

At high intensity, the gain “saturates” and hence is constant:

$$\frac{dJ}{dz} = g_0 J_{sat}$$

Intermediate case interpolates between the two:

$$\frac{dJ}{dz} = g_0 J_{sat} \left( 1 - e^{-\frac{J}{J_{sat}}} \right)$$
Single-pass Amplification

Math

This differential equation can be integrated to yield the Frantz-Nodvick equation for the output of a saturated amplifier:

$$J_{out} = J_{sat} \log \left\{ G_0 \left[ \exp \left( \frac{J_{in}}{J_{sat}} \right) - 1 \right] + 1 \right\}$$

where the small signal gain per pass is given by:

$$G_0 = \exp(g_0 L) = \exp\left( \frac{J_{sto}}{J_{sat}} \right)$$

The gain will be high, or the energy extraction will be efficient, but not both at the same time.
Frantz-Nodvick equation

\[ J_{out} = J_{sat} \log \left\{ G_0 \left[ \exp \left( \frac{J_{in}}{J_{sat}} \right) - 1 \right] + 1 \right\} \]

\[ G_0 = \exp(g_0L) = \exp\left( \frac{J_{sto}}{J_{sat}} \right) \]

So you can have high gain or high extraction efficiency. But not both.
Gain Narrowing

On each pass through an amplifier, the pulse spectrum gets multiplied by the gain spectrum, which narrows the output spectrum—and lengthens the pulse!

As a result, the pulse lengthens, and it can be difficult to distinguish the ultrashort pulse from the longer Amplified Spontaneous Emission (ASE)
Gain Narrowing Example

10-fs sech² pulse in

FWM 65-nm FWHM

Ti:sapphire gain cross section

Factor of 2 loss in bandwidth for $10^7$ gain
Most Terawatt systems have $>10^{10}$ small signal gain
Introduce some loss at the gain peak to offset the high gain there.
Gain-Narrowing Conclusion

Gain narrowing can be beaten.

We can use up to half of the gain bandwidth for a 4 level system.

Sub-20 fs in Ti:sapphire
Sub-200 fs in Nd:glass
Very broad spectra can be created this way.

A 100-nm bandwidth at 800 nm can support a 10-fs pulse.
Heat deposition causes lensing and small-scale self-focusing. These thermal aberrations increase the beam size and reduce the available intensity.

\[ I_{\text{peak}} = \frac{E}{A \Delta T} \]

We want a small focused spot size, but thermal aberrations increase the beam size, not to mention screwing it up, too.

Now the average power matters. The repetition rate is crucial, and we’d like it to be high, but high average power means more thermal aberrations...
Low temperature minimizes lensing.

In sapphire, conductivity increases and $dn/dt$ decreases with $T$.

Calculations for kHz systems

Cryogenic cooling results in almost no focal power

Murnane, Kapteyn, and coworkers
Static Wave-front Correction

2.5 times improvement in peak intensity has been achieved

Before correction
FWHM: 39µm
1.4 times the diffraction limit

After correction
FWHM: 27µm
diffraction limited

With the correction, the energy inside the diffraction limited spot size is multiplied by 2.1 (results taken at low energy).

The simulation allows us to predict our energy distribution at high energy.
Dynamic Correction of Spatial Distortion

Wavefront sensor

interferogram

50 mm diameter
37 actuators

Deformable mirror

Wavefront reconstruction
Computes of the optimal shape of the mirror

Send voltages to the deformable mirror for the correction

CUOS
The pulse has leading and following satellite pulses that wreak havoc in any experiment. If a pulse of $10^{18} \text{ W/cm}^2$ peak power has a “little” satellite pulse one millionth as strong, that’s still $1 \text{ TW/cm}^2$! This can do some serious damage!

Ionization occurs at $10^{11} \text{ W/cm}^2$
so at $10^{21} \text{ W/cm}^2$ we need a $10^{10}$ contrast ratio!
Major sources of poor contrast

Nanosecond scale:
- pre-pulses from oscillator
- pre-pulses from amplifier
- ASE from amplifier

Picosecond scale:
- reflections in the amplifier
- spectral phase or amplitude distortions
Amplified Spontaneous Emission (ASE)

Fluorescence from the gain medium is amplified before the ultrashort pulse arrives.

This yields a 10-30 ns background with low peak power but large energy.

Depends on the noise present in the amplifier at $t = 0$

In a homogeneously broadened medium, ASE shares the gain and the excited population with the pulse.

Amplification reduces the contrast by a factor of up to 10.
Amplified pulses often have poor contrast.

Pre-pulses do the most damage, messing up a medium beforehand.
Amplified pulses have pre- and post-pulses.
A Pockels cell “Pulse Picker”

A Pockels cell can pick a pulse from a train and suppress satellites. To do so, we must switch the voltage from 0 to kV and back to 0, typically in a few ns.

Switching high voltage twice in a few ns is quite difficult, requiring avalanche transistors, microwave triodes, or other high-speed electronics.
Pockels cells suppress pre- and post-pulses.

Unfortunately, Pockels cells aren’t perfect. They leak ~1%. 

\[ \text{10 ns} \]

\[ 10^{-2} - 10^{-3} \]
Contrast improvement recipes

A Pockels cell improves the contrast by a few 100 to 1000.

We need at least 3 Pockels cells working in the best conditions:

- on axis (do not tilt a Pockels cells)
- broad band high contrast polarizers (not dielectric)
- fast rise time (<<2 ns 10-90%)
- collimated beams

Temperature drift is also a problem in Pockels cells.

Also: Good pump synchronization gives a factor 3-10
Multiple-Stage Multi-Pass Amplifiers

4 mJ, 20 fs pulse length

0.2 TW

1 kHz Multi-pass system at the University of Colorado (Murnane and Kapteyn)
High energy, high contrast 100 Hz system at CELIA

10 fs oscillator → stretcher → 100 Hz Regenerative amplifier

Closed loop cryogenic cooling

100K

5 x 1J, 20 Hz Nd:YAG lasers

200 mJ, 30 fs, 100 Hz
Amplified-pulse beam shapes

Pump beam

Ultrashort pulse--near field

Ultrashort pulse--far field
The **Texas High-Intensity Optical Research Laser - The THOR laser**

It is designed to deliver 35 fs laser pulses with energy of 0.7 J, yielding a peak power of 20 terawatts.
Positive Light Multi-Joule Systems

Terawatt Laser System

Ti:sapphire
Energy > 1 Joule
Pulsewidth < 35 fs
Power > 10 TW
Repetition rates to 1 kHz

Nd:Glass
Energy > 20 Joules
Pulsewidth < 500 fs
Power > 40 TW
Repetition rates ~ every hour

You can buy these lasers!
What to do with such high intensities

Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0c^2$

$\Delta \nu_g$: gain bandwidth
$\sigma$: transition cross-section

Laser intensity Limit: $I = (\hbar \nu^3/c^2)(\Delta \nu g/\sigma) = P_{th}/\lambda^2$

Nonlinear Relativistic Optics: $\nu_{osc} \sim c$
(large ponderomotive pressures)

Bound Electrons: $E = e^2/a_o$

- mode-locking
- CPA
- Q-switching

PBWA, LWFA

Pulse energy vs. Repetition rate

- Oscillator
- Cavity-dumped oscillator
- Regen
- Regen + multipass
- Regen + multi-multi-pass
- RegA
- 1 W average power
- Oscillator

Rep rate (pps)

Pulse energy (J)