Femtosecond Technology

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A short pulse is made by interference
There is no choice — it is mathematics

An electron wave packet is similar
An electron wave function is also similar
A very great deal of how we understand optical pulses can be applied to electron wave packets and wave functions.

And visa-versa

*Remember this when you study quantum mechanics*
In linear propagation each mode (or frequency) behaves independently.

For example, each mode has its characteristic phase velocity.

Since no mode can influence another, the only way to synchronize the phase of the modes is through a nonlinear interaction.

We will deal with synchronization in a few minutes.
Not all colors have the same phase velocity

The envelope is caused by interference. It moves with the group velocity

\[ \frac{\partial \omega}{\partial k} \]

The oscillation moves with the phase velocity, \( \omega/k \)

Dispersion occurs in all materials
Since each color is independent, we can correct for dispersion.
**Dispersion Control**

Anything disperses a short pulse since it contains a very large bandwidth of phased radiation.

Dispersion control is possible in:
- prism pairs
- grating pairs
- chirped mirrors

Normal dispersion (phase velocity lower for blue) in material

Anomalous dispersion in the geometry
Correcting more complex dispersion.

Changing the phase of each frequency allows us to reconstitute the pulse.

Usually we use
- a liquid crystal modulator (like on your TV) or
- an acoustic wave that we send through quartz.
In *conventional optical communications* we encode information on the amplitude of pulses such as these.

- Propagation between repeaters is linear.
- Therefore, we can predict and correct the pulse.

In *coherent optical communications* we do not bother to correct. Instead we calculate and measure everything.

*Information is now written on the amplitude, phase and polarization of light.*
In principal the communications network need not care about the dispersion in the many kilometers of fibre that it uses – because it is linear and correctable.

The current communications network corrects for dispersion.

The future network will not.
Application II: Optical Coherence Tomography

Like radar but using light -- therefore micron resolution (a 10 femtosecond pulse is only 3 $\mu m$ long) -- Imagine the resolution offered by attosecond pulses!

But why bother to make short pulses if propagation and measurement is linear.
While it is nice to think of a short pulse, all we really need is wide bandwidth radiation and a reference.
What about intensity?

By concentrating the light we increase the intensity
Nonlinearity -- consider two frequencies

\[ E_{tot} = E_1 \sin(\omega_1 t + \varphi_1) + E_2 \sin(\omega_2 t + \varphi_2) \]

Assume that \( E_1 = E_2 \); \( \omega_1 = \omega - \delta \omega \); \( \omega_2 = \delta + \delta \omega \)

\[ E_{tot} = 2E_1 \sin(\omega t + (\varphi_1 + \varphi_2)/2) \cos(\delta \omega t + \delta \varphi) \]

But a laser stores only so much energy. If we extract it in two modes, they must share this energy (or intensity)
Nonlinearity -- consider two frequencies

Energy shared between two modes so \( I_1 = 1/2 \)

\[ I_{\text{single}} \]

\[ E_1 = \frac{1}{\sqrt{2}} E_{\text{single}} \]

\[ I_{\text{total-Maximum}} \sim 4E_1^2 = 2 I_{\text{single}} \]
Generalizing to n-modes

\[ I_{\text{Total-Maximum}} \sim n I_{\text{single}} \]

By phasing n modes we increase the peak intensity (or power) circulating in the cavity by n times.

In a modern femtosecond laser we can have \( n \sim 5 \times 10^6 \).

**Femtosecond lasers are superb tools for high intensity and nonlinear physics**
Creating femtosecond pulses (mode locking): Making different modes (frequencies or directions) talk to each other

Since laser modes operate independently without nonlinearity, we need nonlinear physics to create short pulses.

Consider a laser oscillator
The ideal “laser”

But some material is needed for a laser

Each round trip a short pulse is distorted – because of dispersion in the laser material (and also mirrors)
But since it is linear propagation, we can correct it.

Whatever the pulse shape, the pulse is reconstituted every bounce.

We have engineered the “ideal laser” but now with material.
Locking the Modes using the Kerr effect

For linear propagation, $V_{ph} = c/\eta$

But at some intensity range this begins to break down

For symmetric materials with no resonances
$V_{ph} = c/(\eta_0 + \eta_2E^2)$

$\eta = \eta_0 + \eta_2E^2$

Different colors and different spatial directions “talk to each other”.
Dispersion is almost completely compensated – while self-focusing/ self-phase modulation modulation continually “chip away” at the pulse every round trip.

Self-phase modulation and self-focussing occur in the Ti:sapphire crystal

Pump beam

Output pulses can be 3 fs (1.1 periods!), 10 nJ, 100 MHz

Discovered by W. Sibbett’s group
Explained by M. Piché (Laval University)
Now you know all tools needed to create the world’s shortest pulses and also highest power pulse – probably the Galaxies most intense light source!

In Russia there are plans for a laser producing $10^{18}$ W! Focussed to a micron we would have $10^{26}$ W/cm². (an Electron becomes relativistic at I $\sim 10^{18}$ W/cm²)

Will the vacuum break down?

CPA -- Discovered in 1985 by Strickland (now at Waterloo) and Mourou (now in Paris)
A few of the applications of nonlinearities

- *Producing short pulses*
- Remote sensing
- *Nonlinear microscopy*
- *Frequency conversion*
- Nano-plasmonics
- Quantum information and cryptography
- New kinds of amplifiers
- Pump-probe spectroscopy
- Laser machining
- X-ray generation
- Imaging mass spectrometry

But in *some ways nonlinearities* are bad for communications network *but in others essential* -- so what we do is very important for communications companies.

Research at uOttawa

* research at the JASLab.
How can we measure something so short?

There are many ways to progress.

• Only a femtosecond pulse itself is short enough to measure a femtosecond pulse.

• We need nonlinearities since we need to compare the phase at different frequencies.
To measure the pulse we must somehow:

1. trace out the field -- Autocorrelator
2. determine the phase relation between different frequencies -- SPIDER
3. A mix of the two -- FROG
We measure $E(t)$ or $E(x)$ with a sheared (nonlinear) interferometer:

**Autocorrelator:** if the detector is a photodiode

**FROG:** if the detector is a spectrograph
Pump-probe spectroscopy and autocorrelation are about the same.

Changing the doubling crystal for a sample of unknown properties, we probe dynamics.
A Nobel Prize winning Idea (Zewail, 1999): Pumped with 310 nm pulse; probed with tunable 600 nm radiation (produced by continuum generation); measuring fluorescence from an excited state.

Watching a molecule decide to dissociate is almost like measuring a femtosecond pulse.
Review:

1. We have seen different applications of short pulses

1. We know how to make short pulses

2. We know how to measure short pulses using a nonlinear interferometer

Can we make similar measurements of electron wave packets and molecular orbitals”?
Remember your Quantum Mechanics

Some argue that orbitals are intrinsically unmeasurable.

Others argue that wavefunctions cannot be measured, only their square.

Attosecond technology allows us to say something about these issues
The fundamental attosecond idea; $F=ma$

Attoseconds first arises here

Ionization

Gaining KE

Like a marble rolling on a teeter-totter

XUV generation - Recombination

Mapped by classical physics to here

300 eV

50 eV

10 eV
A quantum mechanical perspective

A (nonlinear) interferometer made from a molecule’s electrons
Reading the interferometer; Producing High Harmonics/Attoseconds pulses

Amplitude and phase of the re-collision electron are transferred to light through $d(t)$. 

An oscillating charge emits light at the frequency of oscillation.
Electron interferometry or Orbital tomography

We follow similar ideas as those for measuring femtosecond pulses – or for lens-less imaging.

Please read the Max Born 50\textsuperscript{th} anniversary booklet or the original paper.

JASLab, 2012

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