Controlling matter with single-cycle pulses of THz light

Vitaliy Goryashko
2017
What, Why and How

Accelerator physics in Uppsala

Control of matter with THz light
• Overview of low-energy collective excitations
• Switching on and off spin-waves in antiferromagnets
• Switching between conducting and insulating states
• Control of superconducting transport
• THz dynamics in bacteriorhodopsin

Generation of single-cycle THz pulses
• Optical rectification
• Transition THz radiation from e-bunches
• Half-cycle THz pulses from an undulator

Proposal for a THz Light at Uppsala
Uppsala University

**Oldest university in Scandinavia (1477)**

- **Sweden**
  - 10 million (pop.), 450'000 km², 500 GEur (BNP)
- **Uppsala**
  - 25'000 students, 9'000 staff, 630 MEur annual budget
  - faculties of theology, law, medicine, pharmacy, arts, social sciences, languages, educational sciences, science and technology
  - university library and hospital
- **Science and technology**
  - 10'000 students, 1'800 staff
  - historical profiles: Linnaeus, Rudbeck, Celsius, Ångström, Siegbahn, Svedberg
  - R&D areas
    - physics, chemistry, biology, earth sciences, engineering, mathematics, IT
1940's: Theodore Svedberg proposes to build a cyclotron

• Gustaf Werner synchro-cyclotron (1947 – present)
  – nuclear physics & cancer treatment
• CELSIUS ring (1984 – 2005)
  – nuclear physics

• External
  – CTF3/CLIC at CERN (since 2005)
  – FLASH/XFEL at DESY (since 2008)
  – ESS (since 2009)

• FREIA laboratory (since 2011)
• Skandion clinic (2015)
  – cancer treatment
European Spallation Source (ESS), Sweden
The European Spallation Source (ESS)

• Lund, Sweden, next to MAX-IV
  – to replace aging research reactors
  – 2019 first neutrons
  – 2019 – 2025 consolidation and operation
  – 2025 – 2040 operation

• 5 MW pulsed cold neutron source, long pulse
  – 14 Hz rep. rate, 4% duty factor
  – >95% reliability for user time
  – short pulse requires ring, but user demand satisfied by existing facilities (ISIS, SNS, J-PARC)

• High intensity allows studies of
  – complex materials, weak signals, time dependent phenomena

• Cost estimates (2008 prices)
  – 1,5 G€ / 10 years
  – 50% by Sweden, Denmark, Norway
FREIA: Facility for Research Instrumentation & Accelerator Development

State-of-the-art Equipment
- cryogenics
  - liquid helium
  - liquid nitrogen
- control room
  - equipment controls
  - data acquisition

Competent and motivated staff
collaboration of physics (IFA)
and engineering (Teknikum).

Funded by
KAWS,
Government,
Uppsala Univ.

radio-frequency (RF)
power sources

3 bunkers with test stands
horizontal cryostat
vertical cryostat

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Single-cycle THz pulses
Control of matter with THz light
Low-energy excitations: D. N. Basov et al., Rev. of Mod. Phys. 2011
Beauty of ultra-short THz pulses

- direct access to low energy degrees of freedom in complex matter
- below optical transitions – no parasitic effects from optical pump laser pulses
- low heat deposit
- field effects directly in the time domain

<table>
<thead>
<tr>
<th>1 THz</th>
<th>4.1 meV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ps</td>
<td>47.6 K</td>
</tr>
<tr>
<td>300 μm</td>
<td>0.39 kJ/mol</td>
</tr>
<tr>
<td>33 cm⁻¹</td>
<td>0.094 kcal/mol</td>
</tr>
</tbody>
</table>
THz induced magnetization dynamics in NiO

- easy axis (112)
- Neel temperature 523 K
- peak magnetic field of 0.13 T
- time resolution 8 fs

\[ \vec{G} = \gamma \vec{S} \times \vec{B} \]

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Single-cycle THz pulses

T. Kampfrath, Nature Photonics, vol. 5, 2010
Dynamics of spins

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Single-cycle THz pulses
Switching on and off magnons

An induced magnetization $M(t)$ manifests itself by the Faraday effect

$$\theta_F(t) = V d \langle e_k \cdot M(t) \rangle$$
Prediction of spin flipping

Effective Hamiltonian

\[ H = -J \mathbf{S}_1 \cdot \mathbf{S}_2 + \sum_{j=1}^{2} \left[ D_x S_{jx}^2 + D_y S_{jy}^2 \right] + \gamma \mathbf{B}(t) \cdot \sum_{j=1}^{2} \mathbf{S}_j. \]

Landau-Lifshits-Gilbert eq. of motion

\[ \frac{\partial}{\partial t} \mathbf{S}_j = -\frac{\gamma}{1 + \alpha^2} \left[ \mathbf{S}_j \times \mathbf{B}_j^{\text{eff}} - \frac{\alpha}{|\mathbf{S}_j|} \mathbf{S}_j \times (\mathbf{S}_j \times \mathbf{B}_j^{\text{eff}}) \right], \]

Effective magnetic field

\[ \mathbf{B}_j^{\text{eff}} = \mathbf{B}(t) - J \mathbf{S}_{3-j} / \gamma + (D_x S_{jx}, D_y S_{jy}, 0)^t / \gamma. \]
Creating new dynamics states of matter by THz light

Courtesy of A. Cavalleri

1 THz ~ 50 K ~ 4 meV

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Single-cycle THz pulses
Phonon Driven I-M Transition

\[ \text{Pr}_{0.7}\text{Ca}_{0.3}\text{MnO}_3 \]


Conductivity (\(\Omega^{-1}\text{cm}^{-1}\)) vs. Delay (ns)

Vibrational Excitation

Single-cycle THz pulses
Superconducting transport between layers of a cuprate is gated with high-field terahertz pulses, leading to oscillations between superconductive and resistive states, and modulating the dimensionality of superconductivity in the material.

*Andrea Cavalleri group*
Bacteriorhodopsin is a light-driven proton pump

Bacteriorhodopsin acts as a proton pump; that is, it captures light energy and uses it to move protons across the membrane out of the cell.[2] The resulting proton gradient is subsequently converted into chemical energy.
Transformation cycle of bacteriorhodopsin

![Graph showing transformation cycle of bacteriorhodopsin](image)

- **Experimental**
- **Electron transfer**
- **Electron and proton transfer**

**Time (ps)**

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Single-cycle THz pulses
Generation of single-cycle THz pulses
Generation of terahertz pulses by optical rectification

The incoming field $E$ with frequency $\omega$ generates a nonlinear polarization $P$ via the second order nonlinear susceptibility.

$$P_t^{(0)} = \sum_{jk} \chi_{ijk}^0 E_j^\omega E_k^\omega$$

$$\nabla \times \nabla \times \vec{E} + \frac{1}{c^2} \frac{\delta^2}{\delta t^2} (\varepsilon \vec{E}) = -\frac{4\pi}{c^2} \frac{\delta^2 \vec{P}}{\delta t^2}$$

Matthias Hoffmann, [http://mpsd-cmd.cfel.de/research-met-thz-optrect.html](http://mpsd-cmd.cfel.de/research-met-thz-optrect.html)
Moving charge in a medium

\[ v > v_{ph}, \quad \beta > 1/n \]
Phase matching

By tilting the optical pulse front, one achieves coherent build up of a THz wave with a long interaction length.

\[ \cos \gamma = \frac{n_{vis}^{THz}}{n_{ph}} \]

Matthias Hoffmann, [http://mpsd-cmd.cfel.de/research-met-thz-optrect.html](http://mpsd-cmd.cfel.de/research-met-thz-optrect.html)
Single-cycle terahertz pulses with amplitudes exceeding 1 MV/cm generated by optical rectification in LiNbO$_3$
Generation of THz pulses through transition radiation

- **Transition radiation** is produced by relativistic charged particles when they cross the interface of two media of different dielectric constants.

- Since the electric field of the particle is different in each medium, the particle has to "shake off" photons when it crosses the boundary.

The energy emitted in the spectral range $\Delta f$ reads

$$W \approx \Delta \omega \frac{e^2}{\pi c} [2 \log 4\gamma - 1] \quad \gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$
Single-cycle THz pulses at DESY: 1 MV/cm

- Energies up to 100 μJ
- Electric fields up to 1 MV/cm
- A frequency band from 200 GHz to 100 THz

M. Hoffmann et al., Vol. 36, No. 23 / OPTICS LETTERS 4473
Single-cycle THz pulses at FACET/SLAC: 6 MV/cm

23 GeV beam!
Proposal for a THz Light Source in Uppsala
Wish list for intense THz radiation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quasi-half-cycle pulses for time-resolved experiments</th>
<th>Narrowband pulses for frequency-resolved experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range (THz)</td>
<td>1.5-15</td>
<td>1.5-15</td>
</tr>
<tr>
<td>Pulse duration (ps)</td>
<td>0.1-1</td>
<td>1-10</td>
</tr>
<tr>
<td>Pulse energy (mJ)</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>Peak electric field (GV/m)</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Relative bandwidth FWHM</td>
<td>100%</td>
<td>10%</td>
</tr>
<tr>
<td>Repetition rate (kHz)</td>
<td>1-100</td>
<td>1-100</td>
</tr>
</tbody>
</table>

+ Polarization control, pump-probe configuration
The source

- it covers the spectral range from 5 to 15 THz;
- polarization variable from linear to circular or elliptical;
- tunability of the central frequency and bandwidth;
- multi-kilohertz repetition rate;
- light carrying orbital angular momentum.
Single-cycle synchrotron radiation

- Single-cycle THz pulses
Single-cycle radiation from a segmented undulator

undulator segments

e-beam

THz light

enhanced

enhanced
Single-cycle radiation from a segmented undulator: cont’d

Magnetic field of segments

Field Profile

Normalised Radial Distance $r/r_b$
Source 1: quasi-half-cycle pulses
Source 2: multi-cycle pump and single-cycle probe

**Source 2a**

- Field Profile
- Spectrum

**Source 2b**

- Field Profile
- Spectrum

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