テラヘルツ放射光利用の現状と大強度CSRテラヘルツ光への期待

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分子科学研究所UVSOR施設
Outline

- Introduction of UVSOR-II
- IR + THz beamline BL6B at UVSOR-II
  - Optics
  - Performance
- Application
  - THz spectroscopy of large samples
  - THz spectroscopy under high pressures
- Development of Coherent SR at UVSOR-II
- CSR-ERL?
- Conclusion and prospects
Collaborators and acknowledgments

Experiments

- Spectroscopy at high pressures
  - T. Mizuno @ SOKENDAI+UVSOR

- CSR
  - M. Katoh, A. Mochihashi, M. Shimada @ UVSOR
  - M. Hosaka, Y. Takashima @ Nagoya Univ.
  - T. Takahashi @ Kyoto Univ.

Samples

- SmS
  - N.K. Sato, K. Matsubayashi @ Nagoya Univ.

- SmB₆
  - S. Kunii @ Tohoku Univ.

This work was performed at UVSOR and was partially supported by MEXT of Japan.
1 THz = 33 cm\(^{-1}\) = 4 meV
What’s IR&THz synchrotron radiation?

"Infrared" and "THz" synchrotron radiation is a tail of SR.
Properties of IR-SR
(compared to other light sources)

- High brilliance
  - For microspectroscopy
- Very broadband
  - For probing electromagnetic dynamics
- Linear / circular polarization
  - For linear / circular dichroism
- Pulse light (sub-nsec - μsec)
  - For time structure experiments
High brilliance property of IR-SR

Focusing at the sample position of IR microspectroscopy station of BL43IR at SPring-8

Peak intensity of SR is about $10^2$ times higher than that of globar source.

IR-SR is sharper than BB light source.
## IR-SR facilities in the world

<table>
<thead>
<tr>
<th>Country</th>
<th>Facility</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>UVSOR 6B</td>
<td>FIR, multipurpose, high pressure (solid state physics) MIR, multipurpose, IRMCD (solid state physics)</td>
</tr>
<tr>
<td></td>
<td>SPring-8 43IR</td>
<td>MIR&amp;FIR, microscopy under extreme conditions surface science, multipurpose, pump-probe</td>
</tr>
<tr>
<td>USA</td>
<td>NSLS U2A</td>
<td>MIR, microscopy under high pressure (geology)</td>
</tr>
<tr>
<td></td>
<td>U2B</td>
<td>MIR, microscopy for biology</td>
</tr>
<tr>
<td></td>
<td>U4IR</td>
<td>FIR&amp;MIR, surface science</td>
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<tr>
<td></td>
<td>U10A</td>
<td>MIR, multipurpose (solid state physics)</td>
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<tr>
<td></td>
<td>U10B</td>
<td>MIR, multipurpose, wide energy range</td>
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<tr>
<td></td>
<td>U12IR</td>
<td>FIR, pump-probe (solid state physics)</td>
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<tr>
<td></td>
<td>ALS 1.4.2</td>
<td>MIR, multipurpose, surface science</td>
</tr>
<tr>
<td></td>
<td>1.4.3</td>
<td>MIR, microscopy (biology)</td>
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<tr>
<td>SRC</td>
<td>031</td>
<td>MIR, microscopy</td>
</tr>
<tr>
<td>France</td>
<td>super-ACO SIRLOIN</td>
<td>MIR, multipurpose</td>
</tr>
<tr>
<td>UK</td>
<td>SRS 13.3</td>
<td>FIR&amp;MIR, microscopy, surface science</td>
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<tr>
<td>Sweden</td>
<td>MAX I 073</td>
<td>FIR&amp;MIR, high resolution (gas)</td>
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<tr>
<td>Germany</td>
<td>ANKA</td>
<td>Edge radiation</td>
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<td></td>
<td>BESSY II</td>
<td>MIR, microscopy, CSR</td>
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<td>Italy</td>
<td>DAΦNE</td>
<td>SINBAD MIR, FIR</td>
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<tr>
<td></td>
<td>Elletra</td>
<td>MIR</td>
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<tr>
<td>Taiwan</td>
<td>SRRC</td>
<td>MIR, microscopy</td>
</tr>
<tr>
<td>Switzerland</td>
<td>SLS</td>
<td>MIR&amp;FIR microscopy</td>
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<tr>
<td></td>
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<td>MIR, microscopy</td>
</tr>
<tr>
<td>Korea</td>
<td>PLS, China NSRL</td>
<td>under consideration</td>
</tr>
<tr>
<td>China</td>
<td>NSRL</td>
<td>under consideration</td>
</tr>
</tbody>
</table>

Red characters mean FIR is available.
Blue characters mean MIR is only available.
4th International Workshop on
Infrared Microscopy and Spectroscopy with
Accelerator Based Sources

Second Announcement

WIRMS

2007

September 25 – 29, 2007
Awaji-Island, Hyogo, Japan
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UVSOR Facility, Institute for Molecular Science
Reconstructed IR+THz beam line (BL6B) at USOR-II (since 2004)

Acceptance angle of SR
From 80(H) x 60(V) mrad$^2$
To 215(H) x 80(V) mrad$^2$
Magic mirror with vertical focusing


Beam size at emission point

Beam size at focal point (hν~0.5eV)

ρ ≈ 40m

e− beam size:
σx = 0.2mm,
σy = 0.03mm,
σz = 15ps

In an orbital plane

ρ ≈ 40m

Magic mirror

σD = 0.02049

Beam size at emission point

σD = 0.3684

Beam size at focal point (hν~0.5eV)

σD = 0.6307

Horizontal beam size (mm)

Vertical beam size (mm)

Horizontal beam size (mm)

Vertical beam size (mm)
Beam size at the first focal point of BL6B

**Calculation**

\( h \nu = 0.1 \text{eV} \)

**Experiment**

\( h \nu = 0.1 \sim 1 \text{eV} \)

UVSOR Facility, Institute for Molecular Science
**Photon flux and brilliance**

**Photon flux**  
(due to large acceptance angle)

![Graph showing photon flux vs. energy (eV) for different sources: BL6B(IR), old-BL6A1, SPring-8 BL43IR.](#)

**Brilliance**  
(performance of the magic mirror)

![Graph showing brilliance vs. energy (eV) for different sources: SPring-8 BL43IR, BL6B, old-BL6A1.](#)

Si bolometer saturates in a multi-bunch operation!

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**UVSOR Facility, Institute for Molecular Science**
End stations of BL6B at USOR-II

FT-IR (Bruker 66v)
Reflection-absorption station

FT-THz (JASCO FARIS-1)

Spectromicroscopy station

This chamber can be removed for the other experiments (IR-MCD, FIR-RAS and so on).
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Physical properties of SmB$_6$

XPS ($I$(Sm$^{2+}$):$I$(Sm$^{3+}$)=3:7)

Mixed valence

Semiconductor with two gaps ($E_G \sim 5, 17$meV)

Electrical resistivity


Hot carriers in SmB$_6$

BL6B (UVSOR-II) In Lab. (mercury lamp)

Large spectral change is due to the thermally excited carriers across the small energy gap. DOS 17meV

Old data

THz spectroscopy under pressures

Microscope

- Horizontal optical pass
- Energy range
  - Laboratory: 50 meV ~ 1.2 eV
  - UVSOR-II BL6B: 5 meV ~ 50 meV

Diamond anvil pressure cell

- Pressure media: Apiezon grease N
- Pressure is measured by a ruby fluorescence method.

Spatial resolution of microscope in the THz region at BL6B

UVSOR Facility, Institute for Molecular Science
Spatial resolution of THz microscope at BL6B of UVSOR-II

**MIR**
UVSOR-II
+ Ge/KBr
+MCT
(500-8000cm⁻¹)

**FIR (THz)**
UVSOR-II
+ Mylar6µ
+Si bolo.
(50-600cm⁻¹)

Δr ~ 12 µm

Δr ~ 60 µm

UVSOR Facility, Institute for Molecular Science
Physical properties of SmS

NaCl-type crystal structure

- $P < 0.6 \sim 0.8$ GPa:
  - Black phase
  - Semiconductor
    - $E_g \sim 10^3$ K $\sim 86$ meV
    - Ionic crystal with Sm$^{2+}$
- $P < 1.9$ GPa
  - Golden phase
  - Strongly correlated semiconductor
    - $E_g \sim 100$ K $\sim 9$ meV
    - Mixed valence of Sm$^{2+}$ and Sm$^{3+}$
- $P > 1.9$ GPa
  - Magnetic metal with Sm$^{3+}$
Pressure dependence of $R(\omega)$ in SmS

[T. Mizuno et al., in preparation.]

Golden phase

Two phase coexistence?

Two phase coexistence?

Golden phase

Exp.  
Calc.
Scientific program at UVSOR-II BL6B

Electrodynamics of solids @ multi-extreme conditions
- Very low temperature (~0.4K)
- High pressures (~20GPa)
- High fields (~6T)

THz microspectroscopy

FIR-RAS of adsorbed molecules

THz spectroscopy of proteins

THz excitation with coherent SR.
- $10^3$~$10^4$ higher intensity than the present IRSR.
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CSR from relativistic electron beam

Wavelength ($\lambda$)

Electromagnetic wave

Bunch length $\gg \lambda$ → incoherence

Bunch length $\leq \lambda$ → full coherence

→ partial coherence

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How can we make fine structures in electron bunches?

- Spontaneous electron bunch instability.
  - Bursting mode.

- Modulation induced by extra electric fields.
  - Bunch slicing by short-pulse laser.

UVSOR Facility, Institute for Molecular Science
Coherent Terahertz Pulses by Bunch Slicing

UVSOR-BL6B IR Beamline
(S. Kimura et al., AIP Conf. Proc. 705 (2003),

\[ N \cdot f(1/\lambda) \]

- Incoherent SR
- CSR from whole bunch
- CSR from slicing

UVSOR Facility, Institute for Molecular Science
Coherent Terahertz Pulses by Bunch Slicing

Stable and periodic.

The width originates from the InSb hot electron detector response.

The dip is made by laser.

Onset shifts to the lower wavenumber side with increasing pulse width.

This is the evidence of the CSR originates from the dip induced by laser.

Average power of CSR

Commercial THz source

UVSOR-II BL6B

SPring-8 BL431R

UVSOR Facility, Institute for Molecular Science
Observations in the THz Gap: The Josephson-Plasma Resonance of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$

E.J. Singley², M. Abo-Bakr², D.N. Basov², J. Felkes², K. Holldack², H.-W. Hübers³, P. Kuske³, M. C. Martin³, W.B. Peatman³, U. Schade³, G. Wüstefeld³

Fig. 3: Measured $c$-axis polarized near-normal reflectivity of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (upper panel) for various temperatures at or below the superconducting transition temperature, $T_c$. A resonance that shifts with temperature and disappears above $T_c$ is clearly observed. The lower panel shows the calculated reflectivity of a superconductor with a shifting Josephson-plasma resonance.
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CSR-ERL?

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High power CW THz sources

[M. Tonouchi, nature photonics 1, 97 (2007).]
High power CW THz sources

[M. Tonouchi, nature photonics 1, 97 (2007).]
Application of intense THz CSR

• Probe
  – Imaging in a wide spatial region
    • Ex.) Full human body.
  – Near-field microscopy
    • Phase separation of superconducting phase.

• Excitation
  – Nonlinear optics
    • Photo-induced phase transition.
  – Chemical reaction
    • Site-specific excitation.
    • Microwave effect.
An example of THz imaging (QCL, narrow band imaging)

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 18, NO. 15, JULY 1, 2006

Real-Time Imaging Using a 4.3-THz Quantum Cascade Laser and a 320 × 240 Microbolometer Focal-Plane Array

Alan W. M. Lee, Student Member, IEEE, Benjamin S. Williams, Member, IEEE, Sushil Kumar, Qing Hu, Senior Member, IEEE, and John F. Rona

Fig. 1. Experimental setup of terahertz imaging system. Photo shows vanadium oxide microbolometer (courtesy of BAE systems, Lexington, MA). Cutaway depicts alternate reflection mode setup. (Color version available online at http://ieeexplore.ieee.org.)

Fig. 3. Pencil letters written on inside of paper security envelope at visible frequencies. (a) Terahertz transmission mode, (b) one frame, and (c) terahertz reflection mode (20 frames). (d) Visible frequency thumb print and (e) terahertz reflection mode image of thumb of leading author (20 frames). (Color version available online at http://ieeexplore.ieee.org.)
An example of THz imaging
(broad band, multicolor imaging)
Catching T-rays

Physicists created an opening in the FEL beamline to allow Terahertz rays to pass through. Scientific data is gathered in the Terahertz user labs.

Terahertz light is a virtually unused portion of the light spectrum nestled between photonics and electronics. T-rays can "see" more color than humans can as they reflect different colors of light in various patterns, textures, and signatures. T-rays — a safe, non-ionizing form of electromagnetic radiation — can penetrate many solids, but not water or metals.

Physicists at Jefferson Lab's Free-Electron Laser Facility use magnetic fields to coax very short bunches of high-speed electrons into emitting Terahertz beams. These 100 watt terahertz beams are 100,000 times brighter than those produced at any other operating facility in the world.

T-rays add widely to the wave-based technologies — from the telegraph, radio and X-rays to computers, cell phones and medical MRIs — that have defined the last century and a half.

Potential Applications

Security
- fingerprint chemical and biological terror materials in packages, envelopes or air
- find concealed weapons
- locate hidden explosives and land mines

Medical Imaging
- improve medical imaging
- diagnose skin cancer
- spot tooth erosion earlier than x-rays

Communications
- scan buried metal layers in semiconductors
- widen frequency bands for wireless communication
- help airline pilots navigate through fog

Quality Assurance
- count items in packages
- control quality of pharmaceuticals
- detect dangerous flaws in space shuttle components
This proposal was selected in BESAC 20 year BES Facilities Roadmap.
Conclusion and prospects

Present use of THz-SR
- Spectroscopy of solids under low temperature, pressures and magnetic fields.
- Broadband spectroscopy of solids.
- Microspectroscopy of solids, bio-materials etc.

Future -- **Breaking the present concept.**
- Use of intense THz-CSR.
  - Excitation light.
    - Ex.) THz pump - probe experiment of impurities, etc.
  - Advanced Probing.
    - Multicolor wide spatial region imaging.
    - Investigation of the local electronic structure of solids by THz-SNOM.