Lecture 12

Applications and prognosis of coherent soft x-ray lasers. Feasibility of $\gamma$-ray lasers

Outline

- Patterning by Ar$^{+8}$-laser. Lithography and ablation by Ar$^{+8}$-laser (46.9 nm)
- Probing hierarchies in space and time of x-ray applications.
- The decrease of wavelengths of x-ray lasers would increase their applications. $\gamma$-ray lasers?
Outline ctd.

- Anti-Stokes $\gamma$-ray laser.
- Compton scattering $\gamma$-ray sources.
- Concept of annihilation-based $\gamma$-ray laser.
- Understanding $\gamma$-ray lasers requires theory, computations and experiments.
- Perspectives in X-ray quantum optics.
- Understanding x-ray quantum optics requires theory, computations and experiments
- Problems as home assignments
- References
Many applications of x-ray lasers are based on the so-called **water windows**

**Fig. 1** Penetration distances in water and protein for electrons and X-rays. The edges of “water windows” are marked by two vertical red dashed lines (from Soft X-ray Microscopes and Their Biological Applications, Q. Rev. Biophys., 28, 33 (1995)).
Fig. 2 Schema of soft x-ray microscopy of biological objects. The PMMA photo of a HeLa biocell (from Science 247, 1553(1990)).
Soft x-ray reflective microscopy using a Fresnel lens requires an x-ray laser.

**Fig. 3** Schema of the soft x-ray reflective microscopy. Photo of the fringes on the surface of the Si crystal (a) 250 nm (b) 100 nm (from US Patent 5,177,774 (Jan.5, 1993)).
Experimental setup of soft x-ray laser holography made by an x-ray Ne-like (Se XXV) laser

Fig. 4 Schema of the first x-ray laser holography made by using an x-ray Ne-like (Se XXV) laser (from Science 238, 517 (1987)).
Experimental setup of soft x-ray laser interferometry

Fig. 5 Experimental setup of soft x-ray laser interferometry (from Physical Review Letters, 74, 3991 (1995)).
**Mach-Zehnder interferometer using two x-ray gratings for x-ray interferometry**

**Fig. 6** Mach-Zehnder interferometer using two x-ray gratings for x-ray interferometry (from Opt. Lett. 25, 356 (2000)).
Fig. 7 The scanning soft X-ray microscope requires spatially coherent radiation. (a) Interferogram 0.5 ns time moment after 600 ps pick, 0.4 J LIP. (b) Electron density near the target surface vs the distance from the target (from Phys. Rev. Lett. 89, 065004 (2002)).
Experimental setup of face-on soft x-ray laser radiography

Fig. 8 Experimental setup of face-on soft x-ray laser radiography (from Physical Review Letters, 76, 3574 (1996)).
Experimental setup of x-ray laser Thomson scattering

**Fig. 9** Experimental setup of x-ray laser Thomson scattering (from Central Laser Facility Annual Report 2001/2002, 45 (2002)).

TÁMOP-4.1.1.C-12/1/KONV-2012-0005 project
Patterning by $\text{Ar}^{+8}$-laser

![Diagram of X-laser and Lloyd mirror](image)

**Patterning on Lithium Fluoride crystals**

- Fluorescence spectrum of $F_2$ and $F_3^*$ color centers

- Step: 2.4 μm, 1.2 μm, 700 nm

- Prague, 2005


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**Fig. 10** Patterning by $\text{Ar}^{+8}$-laser (from L’Aquila U., Italy).
Lithography and ablation by $Ar^{+8}$-laser (46.9 nm)

Fig. 11 Lithography on PMM resists and ablation of $SiO_2$ by $Ar^{+8}$-laser (from U. of L’Aquila, Italy)

TÁMOP-4.1.1.C-12/1/KONV-2012-0005 project
Fig. 12 Probing hierarchies in space and time (from www.coe.berkeley.edu).

Probing in space and time. Perspectives (B)

**Fig. 13** Probing hierarchies in space and time (B) (from www.coe.berkeley.edu).

<table>
<thead>
<tr>
<th>Spatial scale</th>
<th>Energy/time scale</th>
<th>Phenomenology</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 nm</td>
<td>~1 eV, 1 fsec</td>
<td>crystal field, intra-atomic exchange and multiplets</td>
</tr>
<tr>
<td>1-2 nm</td>
<td>1-100 meV, 100 fs – 1 ps</td>
<td>t-J-ology; charge, spin, orbital order; polaron, magnons, orbitons, …</td>
</tr>
<tr>
<td>10-1000 nm</td>
<td>&lt; 1 neV? &gt;1 µs?</td>
<td>Mesophase separation; Percolation; domain switching</td>
</tr>
</tbody>
</table>


**Kuwahara and Tokura,** in CMR, Charge Ordering and Related Properties of Manganites, p. 217.

**Example:** CMR manganites

*Surprise! Soft x-rays provide the tools to probe this entire hierarchy!*
Decrease of wavelengths of x-ray lasers would increase their applications → γ-ray lasers

Building on work conducted in the last two decades, research has continued on the release of energy on demand from energetic spin isomers [1, 2]. The early work on a gamma-ray laser led to the first triggered release of stored isomorphic state energy in $^{180}$Ta$^{m1}$ [3]. This result has been observed in subsequent confirming experiments in a number of laboratories around the world [4–8]. Interest in this research is motivated in part by the potential for energy storage in high-energy density material that can be of the order of a megajoule per milligram [9].

There has been continuing interest in Mössbauer effect variants of models that arguably could lead to a gamma-ray laser. These ideas stem from the earliest concepts of such devices. The requirement for very low temperature and over 30 years of research have somewhat dampened interest in the ideas, and successful accomplishment of induced gamma emission has so far been elusive. A significant difficulty has been how to resolve the problem of recoil in a solid lattice while retaining energy coherent emission from nuclei in a solid state medium. To avoid this problem, there have been studies of ways in which lasing without inversion or with hidden inversion might be realized and in the possibility that a gamma-ray laser could be created in cooled particle beams [10, 11].

An alternative and perhaps somewhat more tractable idea of the use of linear arrays of cooled atoms has been suggested [12]. This approach might take advantage of laser cooling of atoms that has been much advanced by a number of groups, and would also make use of advances in triggered emission of gamma radiation from spin isomers.

From [2]
Anti-Stokes $\gamma$-ray laser

**Fig. 14** Schematic diagram for the anti-Stokes transition (from [3]).

**Fig. 15** Decay diagram for $^{179}\text{Hf}$ (from [3]).
Compton scattering $\gamma$-ray sources (A)

Compton scattering sources, which have been widely studied over the past decades (Esarey et al., 1993; Hartemann & Kerman, 1996; Leemans et al., 1997), rely on energy-momentum conservation, before and after scattering. The energy of the scattered photons, $E_x$, depends on several electron and laser beam parameters:

From [4]:

$$E_x = \frac{\gamma - \sqrt{\gamma^2 - 1} \cos \phi}{\gamma - \sqrt{\gamma^2 - 1} \cos \theta + \lambda_0 (1 - \cos \theta \cos \phi + \cos \psi \sin \theta \sin \phi)} E_L$$

where $\gamma$ is the electron relativistic factor, $\phi$ is the angle between the incident laser and electron beams, $\theta$ is the angle between the scattered photon and incident electron, $\psi$ the angle between the incident and scattered photon, $k_0 = 2\pi/\lambda_c$ is the laser wavenumber (reduced Compton wavelength $\lambda_c = 3.8616 \times 10^{-13}$ m), and finally $E_L$ is the laser energy.

Fig. 16 Example of a spectrum simulated with Mathematica, using $10^5$ particles and 100 bins for an electron beam energy of 116 MeV and a laser wavelength of 532 nm. The other parameters are $j = 2$, $\epsilon_x = 5$ mm mrad, $\epsilon_y = 6$ mm mrad, $\sigma_x = 35$ $\mu$m and $\sigma_y = 40$ $\mu$m. (from [4])
Compton scattering γ-ray sources (B)

Fig. 17 Block diagram of the Velociraptor compton source with details of the laser systems. (from [4])

Fig. 18 On axis spectrum recorded after scattering off the Al plate and corresponding Monte Carlo simulation. The images correspond to the full beam and the signal transmitted through the collimator, respectively. (from [4])
Concept of annihilation-based γ-ray laser

Fig. 19 Annihilation γ-laser concept. Positrons from a storage device are suddenly deposited in a tube several centimeters long and a few microns in diameter. The positrons form triplet positronium atoms that quickly cool to a few thousand degrees C and form a Bose-Einstein condensate. A microwave burst converts the positronium to the singlet state and a spontaneous annihilation photon that happens to propagate along the tube is amplified via stimulated emission to form a powerful coherent beam of annihilation photons (from [5])
Understanding $\gamma$-ray lasers requires theory, computations and experiments.
Perspectives in x-ray quantum optics

Let me show the perspective topics related to x-ray quantum optics, which were recently discussed in Ref. [6]

1. Individual photons and photons correlations
   1.2 Parametric down conversion (PDC). Possible applications of X-ray PDS.
   1.3 Single-photon superradiance
   1.4 Collective Lamb shift
   1.5 Coherent control of nuclear forward scattering
   1.6 Generation of entangled X-ray photons

2. Strong coupling X-ray quantum optics
   2.1 Coherent γ-ray radiation via electromagnetically induced transparency for nuclear transitions
   2.2. Electromagnetically induced transparency via cooperative emission in a cavity that contains resonant nuclei
   2.3 Control of the cooperative branching ratio of a given nuclear state
   2.4 X-ray FEL-based nuclear quantum optics
   2.5 Stimulated-Raman-adiabatic-passage (STIRAP) for transfer of population between long-lived states of nuclear isomers

3. Intense-field X-ray quantum optics
   3.1 Resonance fluorescence
   3.2 Laser-dressed Auger decay
   3.3 High-order harmonic generation manipulated by XUV/X-ray light
   3.4 X-ray absorption by laser-dressed atoms
   3.5 Parametric γ-generation

Understanding *x-ray quantum optics* requires theory, computations and experiments.

![Diagram](image)

**Fig. 21** Understanding x-ray quantum optics requires theory, computations and experiments.
Problems as home assignments (A)

1. Describe the advantages of the applications of x-ray lasers for the interferometric testing of soft x-ray multi-layer optics.
2. Describe the advantages of the applications of x-ray lasers for testing of patterned polymer photoresists. Consider the reflective mask for soft x-ray lithography.
3. Point out the advantages of the applications of the capillary Z-pinch Ar+8-laser (U. of L'Aquila, Italy) for lithography on PMM resists and ablation of solids.
4. Explain the use of coherent soft X-ray scattering for the soft x-ray hologram (analyze the experimental hologram obtained at the wavelength 1.59 nm).
5. Explain why a scanning soft x-ray microscope requires spatially coherent radiation.
6. Why would the decrease of wavelengths of soft x-ray lasers increase their applications?
7. Describe soft x-ray microscopy and cryo x-ray tomography.
8. How can magnetic domains be imaged at different x-ray photon energies?
9. Why is the imaging of ultrafast spin dynamics possible with magnetic soft x-ray microscopy?
Problems as home assignments (B)

11. Why are x-ray lasers suitable for the analysis of advanced IC devices by x-rays?
16. Describe probing hierarchies in space and time.
17. Compare briefly x-ray scattering, resonant x-ray scattering and dynamic x-ray scattering.
18. Describe features of coherent soft-x-ray scattering.
19. Consider the static coherent soft X-ray “Speckle metrology” of thin film ferromagnets.
20. Explain the relation: Coherence of soft x-rays $\rightarrow$ correlations $\rightarrow$ complexity.
21. Explain the statement: The decrease of the wavelengths of x-ray lasers would increase their applications $\rightarrow$ $\gamma$-ray lasers.
22. Explain the physical principle of Anti-Stokes $\gamma$-ray laser.
23. Explain Compton scattering $\gamma$-ray sources (lasers).
24. Give a concept of the annihilation-based $\gamma$-ray laser.
25. Why does understanding $\gamma$-ray lasers require theory, computations and experiments?
References

7. Application of soft x-ray lasers, S Hatae* and G J Tallents, Univ. of York, UK.

For additional information see: