Energy and Technology Review

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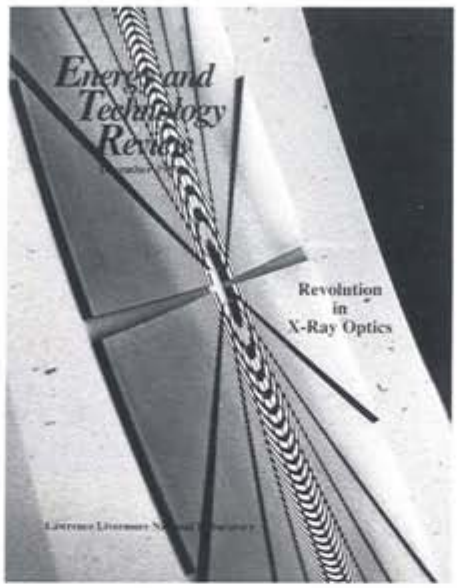
Revolution in X-Ray Optics

Lawrence Livermore National Laboratory



About the Cover

The cover shows a scanning electron microscope image of a Fresnel zone plate — a focusing lens for x-rays (see Figure 5, p. 14). This zone plate structure was fabricated and imaged by Gary Stone of the LLNL Laser Program.

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About the Journal

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. Since then, we have added other major programs, including laser fusion, laser isotope separation, free-electron lasers, biomedical and environmental sciences, and applied energy technology. These programs, in turn, require research in basic scientific disciplines, including chemistry and materials science, computer science and technology, engineering, and physics. The Laboratory also carries out a variety of projects for other federal agencies. *Energy and Technology Review* is published monthly to report on unclassified work in all our programs. A companion journal, *Research Monthly*, reports on weapons research and other classified programs. Titles of recent articles published in *Energy and Technology Review* are listed at the back of the journal. Please address any correspondence concerning *Energy and Technology Review* to Mail Stop L-3, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551.

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Preface

The field of x-ray optics is undergoing a period of revolutionary progress, in which Lawrence Livermore National Laboratory is a leading participant. That is the premise of this special issue, which is a digest of an invited review article recently published by LLNL scientist N. M. Ceglio in the first issue of the new *Journal of X-Ray Science and Technology*.

The Laboratory has been a major contributor to and has benefitted from the revolution in x-ray optics. The Laboratory's contributions in x-ray lasers, x-ray holography, and x-ray optical component and detector development have been well documented in the technical literature, and have been recognized by our receipt over the past five years of eight R&D 100 awards in x-ray optics technology:

1985	Time-Resolved Imaging X-Ray Spectrometer
1986	X-Ray Beamsplitter
1987	Zone-Plate-Coded Microscope
	Highly Dispersive X-Ray Mirror
1988	X-Ray Laser Cavity
	3D Chemical X-Ray Microscope
1989	Reflective X-Ray Mask for Projection X-Ray Lithography
	Multilayer Diffraction Grating

Over the years, *Energy and Technology Review* has documented some of the Laboratory's contributions in x-ray optics, notably in the special dedicated issues of November 1985 (X-Ray Laser) and November/December 1987 (Synchrotron Radiation). Most recently, two articles on x-ray optics appeared in our December 1988 issue.

The present special issue is an attempt to draw a broader perspective on the field and its progress, emphasizing its international scope. The Laboratory's contributions are discussed in that context. In particular, the discussion presents one scientist's view of the recent evolution of the field. Others may, of course, hold different opinions about the relative importance of the specific advances and applications chosen for review. However, about the main point there is no disagreement: in x-ray optics the revolution has begun and is speeding into an exciting future.

Alan K. Burnham
Scientific Editor

The Signs of Revolution

Technological revolutions often proceed unrecognized even by specialists in the field, since they are typically too busy keeping up with the pace of change to develop a global perspective on the process. However, there are often telltale signs: there is acceleration in the rate of progress by many research teams at different institutions, culminating in virtually simultaneous achievement of long-sought-after breakthroughs — a condition transcending conventional technological change. This indicative pattern of events has occurred in the field of x-ray optics twice in recent years, leading to announcements of the x-ray laser in 1984 and of the x-ray hologram in1987.

An X-Ray Laser is Developed at Livermore

New York Times, October 30, 1984

Progress with X-Ray Laser Announced by Two Teams

Boston Globe, October 30, 1984

Researchers Develop "Landmark" X-Ray Lasers

Christian Science Monitor, October 30, 1984

T.H. Maimon's demonstration of the first optical laser in 1960 kindled interest in a number of laboratories internationally and work was begun to develop a laser operating at x-ray wavelengths. The advantage of shorter wavelengths for microscopy, solid-state and surface physics, metrology, and atomic and plasma physics was quickly appreciated. For a long time progress was slow, almost tedious, and much of the early optimism dissipated. Then, almost a quarter century later, not one but two teams announced simultaneously—seemingly out of nowhere—that they had produced copious amounts of amplified spontaneous emission at soft-x-ray wavelengths. These two teams worked totally independently on opposite coasts (one at the University of California, Lawrence Livermore National Laboratory, the other at Princeton University), and they used very different inversion schemes.

X-Ray Holograms May be Boon for Cell Research

San Francisco Chronicle, October 23, 1987

Scientists Working to Unmask the Microworld

San Francisco Examiner , October 23, 1987

Holographic Images May Display Hidden Life Processes

New York Times, December 1, 1987

Dennis Gabor first proposed holography as a lensless technique for high-resolution electron microscopy over 40 years ago. The value of holography for x-ray microscopy was quickly realized, and by 1950 Paul Kirkpatrick and his students were already producing theses and scientific papers on the subject. Other research groups around the world also picked up on the potential of x-ray holography. There was a great deal of excitement. With time, however, progress began to slow, and the work seemed to be going nowhere. Then, in 1987, x-ray holography became an exciting topic once again. Two separate groups working totally independently, on opposite coasts, using quite different optical schemes (one group used an x-ray laser at LLNL in California, the other used a synchrotron undulator at Brookhaven National Laboratory in New York) announced in the same issue of *Science* significant breakthroughs in the development of x-ray holography.

Revolution in X-Ray Optics

The past half-decade has witnessed extraordinarily rapid progress in our ability to generate, manipulate, control, and detect x-rays, leading ultimately to the resolution of the decades-old challenges of x-ray lasers and x-ray holography. We review the recent progress in the field and pose the question: Why is this happening now?

For further information contact N. M. Ceglio (415) 422-8251.

Early researchers in the field of x-ray optics, photographed in the fall of 1981 at a synchrotron conference at Brookhaven National Laboratory. Left to right: Günter Schmahl, O. Christ, B. Niemann (University of Göttingen—x-ray microscopy team), Nat Ceglio (LLNL), Dietbert Rudolph (University of Göttingen), David Attwood (formerly LLNL—presently director of Center for X-Ray Optics, Lawrence Berkeley Laboratory), Arthur Robinson (formerly with *Science* magazine—presently with the Advanced Light Source at Lawrence Berkeley Laboratory), and Hector Medecki (LLNL).

Why, after decades of work in x-ray lasers and x-ray holography, are we only now witnessing an extraordinary acceleration in the rate of progress by a number of research teams across a broad technological front?

Looking closely at these breakthroughs, we find they resulted not from any fundamentally new understanding of short-wavelength processes or from new intellectual breakthroughs in atomic physics or optics. Rather, they are the products of a radical change in the technological landscape.

Specifically, the 1980s revolution in x-ray optics has benefitted enormously from a historic convergence of seemingly unrelated technological advances made in the 1960s and 1970s. For example, development of the x-ray laser drew heavily from the high-power, subnanosecond, optical-laser technology of the 1970s. New high-brightness undulator sources, so important for x-ray holography and microscopy, are descended directly from the synchrotron accelerator technologies developed in the 1960s and 1970s. Our ability to fabricate x-ray optical components (lenses, mirrors, beamsplitters, etc.) is a direct spin-off from the microfabrication technology developed in the 1970s and 1980s for the semiconductor electronics industry.

Another driving force in x-ray optics has been the rapidly advancing field of cellular and subcellular microbiology, which in turn has been driven by a demand for advances in disease control and genetic engineering. Microbiologists have for decades wanted to be able to observe, in real time and on the scale of nanometers, the *function* and *interaction* of *living* cellular and subcellular biological systems. Such observations cannot be achieved by means of electron or visible-light optics, but they are realizable challenges for soft-x-ray optics.

In brief, the field of x-ray optics is in the midst of a period of extraordinary progress, allowing us to address and resolve problems that are many decades old. This progress is made possible by a changed technological landscape, resulting from seemingly unrelated advances in high-power optical lasers, synchrotron accelerators, semiconductor electronics, and microbiology.

In this article we present a detailed (but not exhaustive) review of recent advances in x-ray optics and their applications. In the first section we review advances in high-brightness x-ray sources, new optical components, and advanced detection

Glossary of Terms

Fresnel zone plate (FZP)

A circularly symmetric array of annular zones that are alternately transparent and opaque (see Figure 5, p.17). The FZP acts as a narrowband diffractive lens able to focus x rays to a spot size roughly equal to its outermost zone width.

Fresnel phase plate (FPP)

Has the same geometry as the FZP, but differs in that, instead of opaque zones, the FPP has transparent zones that produce a π phase shift in the transmitted radiation. This results in a focusing lens that has fewer losses and can be as much as four times more efficient than an FZP.

Isoelectronic sequence of ions

A group of ions with differing atomic number Z but the same number of orbital electrons. For example, neon-like selenium ($Z = 34$), strontium ($Z = 38$), and molybdenum ($Z = 42$) all have ions with ten orbital electrons. They may be viewed as members of an isoelectronic sequence. Their importance for x-ray laser design arises from the fact that they all have similar energy level transitions (see Figure 1, p. 8).

Radiometric and photometric nomenclatures

Optical engineers have been very careful in the definition of a system of quantities and units to describe and compare sources of electromagnetic (EM) radiation. Physicists, however, have not adhered closely to the system when characterizing new sources of radiation. For example, the terms **brightness** and **bright**—which strictly refer to a photometric quantity, having meaning only in the visible part of the EM spectrum—are often used in this text to describe x-ray sources with a high spectral radiance. We have tried to be careful about radiometric terminology at least in the figures, where quantitative data are presented. In these cases the specific quantities used are defined below:

Spectral radiant intensity

The energy radiated per unit of time, per unit of wavelength, per unit of solid angle (W/nm·sr). It would, for example, be the appropriate measure of the x-ray laser power (energy/time), radiated in a particular bandwidth (per unit wavelength), into the acceptance solid angle (per unit solid angle) of the time-resolved imaging spectrometer (see Figure 2, p. 9).

Spectral radiance

The energy radiated per unit of time, per unit of source surface area, per unit of wavelength, per unit of solid angle ($W/cm^2 \cdot nm \cdot sr$). The spectral radiance breaks down a source into its fundamental characteristics and is often used to compare different types of sources (see Figure 4, p. 14).

"Bright" or "High brightness" sources

As used in this text, these terms generally refer to x-ray sources of high spectral radiance. Strictly, this is a loose (if common) usage of the terminology.

systems. The second section reviews current work in three high-profile areas of application: x-ray laser cavities, x-ray microscopy, and x-ray holography. In the third section, we preview emerging applications that could redefine the field of x-ray optics (e.g., a high-intensity x-ray laser); these applications could also have significant economic impact and could affect national security (e.g., soft x-ray projection lithography). The final section discusses the likely near-term achievements in x-ray optics, along with a philosophical perspective of what it will take to keep the revolution alive.