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MASTER

Advances in Transmission X-ray Optics*

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Abstract

Recent developments in x-ray optics are reviewed. Specific advances in coded aperture imaging, zone plate lens fabrication, time and space resolved spectroscopy, and CCD x-ray detection are discussed.

Introduction

The rapid development of x-ray optics and the important role played by microfabrication technology has been an active topic of review in recent years¹. This paper is intended as an update to the comprehensive body of review literature on x-ray optics. The past 12-24 months have produced significant technological contributions, which are advancing x-ray optical capabilities along a broad front. Specific advances reported here are in the areas of coded aperture imaging, x-ray lens development, time and space resolved x-ray spectroscopy, and CCD x-ray detection. This work has involved LLNL personnel as well as the collaborative efforts of researchers from other institutions: IBM's Thomas J. Watson Research Center; Cornell University's National Research and Resource Facility for Submicron Structures; MIT's Center for Space Research; MIT's Submicron Structures Laboratory; the University of Rochester's Laboratory for Laser

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Energetics; and Purdue University's Department of Mechanical Engineering.

Recent theoretical work² in coded aperture imaging has extended our understanding of the basic principles of Zone Plate Coded Imaging (ZPCI). An eigenfunction analysis of continuous source distributions has provided new insight to linear as well as nonlinear effects in the microscopy of small laboratory x-ray sources. In addition, the development of new techniques for the fabrication of ultra-thick zone plate coded apertures has extended high resolution coded imaging to shorter wavelength radiations³ (e.g. 100 keV x-rays).

Significant new work has been done in the fabrication of advanced zone plate lensing elements for x-rays. Sophisticated scanning electron beam lithographic (SEBL) techniques⁴ have been applied to the production of Fresnel zone plate objective lenses with minimum linewidths as small as 1500Å. SEBL techniques have also been applied to the production of "large" diameter (21mm) Fresnel zone plate condenser lenses for use in x-ray microscopy⁵. In addition, a detailed design strategy for x-ray phase lenses (i.e. Fresnel phase plates) has been carried out, and the first x-ray phase lens (for use at Al K_{α} = 1.5 keV) has been fabricated⁶.

New capabilities in time and space resolved x-ray spectroscopy have emerged from the coupling of high precision x-ray transmission gratings⁷ with x-ray streak cameras⁸ and grazing incidence reflection (GIR) x-ray microscopes⁹. These new instruments have been applied to the investigation of laser produced laboratory plasmas with striking results¹⁰.

A collaborative effort¹¹ is underway for the development and fabrication of a CCD camera for direct x-ray recording. This instrument will provide a capability for real-time, spatially resolved x-ray detection with high sensitivity and low noise. It offers significant advantages for x-ray microscopy and spectroscopy at low signal levels.

In the following sections each of these topics is discussed in greater detail.

Coded Imaging

Coded imaging, first proposed by Mertz in the 1960's, is a two-step imaging technique¹². In the first step, source information is recorded (encoded) by simple geometrical shadowcasting through a coded aperture. In the second step, image reconstruction (decoding) is achieved using a numerical or optical procedure matched to the coded aperture design. When the coded aperture design is a Fresnel zone plate, image decoding may be achieved by coherent optical reconstruction. In this case the entire imaging process can be viewed as a form of Fresnel transform microscopy, the spatial analog of Fourier transform spectroscopy. This point of view is based on the appreciation that the process of shadowcasting through a Fresnel zone plate may be mathematically represented as a Fresnel transform. The subsequent optical reconstruction of the shadowgraph (Fresnel diffraction) may also be represented as a Fresnel transform. This perspective has particular value, since the eigenfunctions of the Fresnel transform are well known¹³. In particular, the Gaussian-Laguerre polynomials in polar coordinates form a complete, orthogonal set that retain their functional form when Fresnel transformed. Therefore, when a source is represented as a superposition

of Gaussian-Laguerre polynomials, all the integrals in the coded image recording and reconstruction process can be analytically evaluated, and a generalized expression for the reconstructed image in any order can easily be found.

A number of useful insights have emerged from the eigenfunction analysis of continuous source distributions. These are summarized below and discussed in greater detail in reference (2):

- (i) In order to achieve ZPCI with good S/N and negligible background effects it is necessary that the characteristic large scale dimension of the source be less than the diameter of the central zone of the coded aperture.
- (ii) For continuous sources of finite size, tomographic resolution worsens with increased order number. In particular, the tomographic resolution element increases linearly with order number.
- (iii) In the image reconstruction process the focussed intensity into a given image order varies inversely as the fourth power of the order number.

In addition to contributions to the linear theory, the eigenfunction analysis has been used to numerically simulate nonlinear effects in ZPCI cases of practical interest. The results of several simulations are shown in Figs. (1-4). Each figure shows: (a) a radial lineout of the calculated shadowgraph exposure; (b) the nonlinear relationship used to map exposure to amplitude transmittance of the coherently illuminated coded image; and (c) a comparison between the scaled first order image (i.e. reconstructed source) and the original source. With the exception of Fig. 3, imaging errors introduced by nonlinear effects do not influence image integrity. Source widths and amplitude ratios are not altered by more than a few percent. The largest imaging error is in Fig. 3, where the low level exposure is severely clipped by threshold effects

in the shadowgraph recording film. In this case the nonlinearity results in a 15% error in the apparent FWHM of the source. These and other simulations demonstrate that, so long as severe film nonlinearities are avoided, the linear reconstruction terms dominate, and the optically reconstructed first order image is an accurate representation of the source.

Zone Plate Coded Imaging has been used extensively for the microscopy of laser driven fusion targets¹⁴. Progress in this field has led to requirements for imaging capabilities at shorter x-ray wavelengths. This necessitates the fabrication of thick, micro-Fresnel zone plates sufficiently opaque to produce high contrast shadowgraphs suitable for optical reconstruction. Such zone plate coded apertures have been fabricated using reactive ion etch techniques, and used to image 100 keV x-rays with a higher order resolution $\sim 4\mu\text{m}^3$. The coded aperture used in these experiments was a free-standing, 75 μm thick, gold zone plate with a total of 100 zones, and 30 μm minimum zone width. Data from the 100 keV test experiments are presented in Fig. 5. Shown are: (a) the coded image produced by the 100 keV 'point' source; (b) a 1-D linear plot of image intensity along a line through the center of the 100 keV point image; and (c) a 3-D representation of the point response data.

Advanced X-ray Lensing Elements

Among the areas of primary interest in x-ray lens development are improvements in spatial resolution, radiation collection efficiency, and x-ray diffraction efficiency. Improved spatial resolution requires the production of narrow linewidth zone plate objective lenses. Significant

progress in this area has been made at IBM's Thomas J. Watson Research center⁴. An advanced SERL system has been used to generate Fresnel zone plate master patterns with linewidths as small as 1500Å. The system has 16 bit D/A converters and a polar coordinate vector scan capability provided by a 'hard-wired' polar $\leftrightarrow$ rectangular coordinate converter. A zone plate pattern generated by this system is shown in Fig. 6. It has a total of 100 zones, 24 radial support struts, a minimum zone width of 1500Å, and an overall diameter of 60 μ m. This pattern has been made into an x-ray lithography mask, and replicated to produce free-standing zone plate objective lenses.

Improved radiation collection efficiency requires the production of large diameter, multi-zone, Fresnel condenser lenses. Significant progress in this area has been made at Cornell University's National Research and Resource Facility for Submicron Structures⁵. A vector scan SERL system has been used to generate Fresnel zone plate condenser lens patterns with overall diameter approaching 1mm. Shown in Fig. 7 is a condenser lens master pattern of 450 zones with $\sim$ 4500Å minimum zone width, and $\sim$ 0.8mm overall diameter. The edge structure of the outermost zones in Fig. 7 arises from the rectangular coordinate format of the vector scan system and the field quantization limitations of the 13 bit D/A converters.

Increased x-ray diffraction efficiency can be achieved in Fresnel structures by the judicious use of phase effects^{15,16}. In particular, if the material and thickness of the solid zones are chosen to produce negligible absorption and a phase shift of π radians, a first order diffraction efficiency as high as 40% can, in principle, be

achieved. For a material having refractive index, $n = 1 - \epsilon + i\beta$, the appropriate thickness for the phase shifting zones is

$$\Delta r = \frac{\lambda}{2\epsilon}$$

In passing through a phase shifting zone the local x-ray intensity is reduced by the factor $e^{-2\pi\eta}$, where

$$\eta = \frac{\beta}{\delta}$$

is the attenuation parameter upon which lens efficiency solely depends.

η and Δr are the critical parameters in phase lens design. η determines lens efficiency and must be much less than unity for significant phase enhancement of efficiency. Δr is restricted by practical fabrication limitations on high aspect-ratio ($\Delta r/\Delta r$) micro-structures. Figure 8 illustrates a simple scheme for phase lens design. Shown are overlaid curves of Δr and η versus x-ray energy for a silver phase lens. The curves are overlaid such that chosen upper limit values for Δr and η coincide. In this case, we required $\Delta r \leq 1 \mu\text{m}$ (a submicron Δr is presumed), and $\eta \leq .175$ (leading to a first order diffraction efficiency $> 25\%$). Only at those x-ray energies for which both η and Δr lie below the common upper-limit-line can a high resolution, 'reasonably efficient', x-ray lens be fabricated.

A high resolution Fresnel phase plate designed for operation at the Al K_{α} line ($E_x \approx 1.5 \text{ keV}$) has been fabricated⁶. The phase lens, shown in Fig. 9, is made of silver approximately $0.55 \mu\text{m}$ thick. It has a total of 100 zones with a minimum zone width of $3200\text{\AA}$ ¹⁷.

Its calculated operating characteristics at 1.5 keV are as follows:

Attenuation Parameter : $\mu \approx 0.16$
 Energy Fraction in First Order Focus : $\epsilon_1 \approx .26$
 Energy Fraction in Zeroth Order : $\epsilon_0 \approx .04$
 Energy Fraction Absorbed : $\epsilon_{ab} \approx .32$
 Energy Fraction in Other Orders : $\sum \epsilon_j \approx .38$
 Spatial Resolution : $\delta \approx 0.4 \mu\text{m}$
 f/number : $f^\# \approx 337$

Time and Space Resolved X-ray Spectroscopy

X-ray transmission gratings with sub-micron spatial period are attractive dispersion elements for time and space resolved spectroscopy. Because of their simple geometry and broad spectral range, they are easily coupled with instruments of high temporal or spatial resolution. In particular, a free-standing x-ray transmission grating with 3000Å period has been coupled with a soft x-ray streak camera as illustrated in Fig. 10. This time resolved x-ray spectrometer¹⁰ measures continuous x-ray spectra with excellent temporal resolution ($\Delta t \approx 20\text{psec}$) and moderate spectral resolution ($\Delta\lambda \approx 1\text{Å}$) over a broad spectral range (2Å - 120Å) with high sensitivity and large information recording capacity. It has been used to investigate the temporal variation of soft x-ray spectra from laser irradiated targets. A typical data set from these experiments¹⁰ is presented in Fig. 11. Shown are: (a) the direct photographic streak record (x-ray wavelength vs time); (b) the unfolded x-ray source spectra at two different times (accounting for instrument response function); and (c) the time history of target emission in spectral bands centered at 150 ev and 500 ev, as well as that of the total, undiffracted emission.

In addition to time resolved spectra, x-ray transmission gratings have been used to provide spatially resolved spectra from laser driven fusion targets¹⁰. As illustrated in Fig. 12, an x-ray transmission grating has been coupled with a GIR x-ray microscope to produce an imaging spectrometer of broad spectral range ($\sim 0.3 - 4$ keV), high spatial resolution

($\sim 3 \mu\text{m}$), and moderate spectral dispersion $\frac{d\theta}{d\lambda} \sim 3.3 \times 10^{-4} \frac{\text{rad.}}{\text{\AA}}$

This versatile diagnostic capability allows spatial localization of spectrally distinct emissions from laser compressed targets. Figure 12 shows, for example, the spatially localized emission from the compressed argon fill gas of a laser fusion target¹⁸ (shot #7668). The zeroth order microscope image shows that without spectral dispersion the argon feature would be lost amidst the strong, low energy emission from the surrounding glass shell. Such spectrally resolved image data allow us to address issues of implosion dynamics, shell stability, and mix in laser fusion experiments.

X-ray CCD Camera

A balanced development program in x-ray optics must not overlook the significant advantages that can accrue from improvements in x-ray detection. Advances in micro-electronic technology have, in recent years, had important impact on solid state x-ray detectors. In particular, newly developed charge-coupled devices (CCD's) offer low noise electronic x-ray detection with high sensitivity, good spatial resolution, real-time read out, and extreme positional stability¹⁹. Such devices provide

significant advantage over x-ray film with its combined problems of quality control, high grain noise, limited sensitivity, and slow data turn around.

We are involved in a collaborative effort¹¹ for the development and implementation of a CCD camera for direct x-ray imaging. Design specifications for the camera are as follows: It will initially operate in an energy range from 1.5 keV to 15 keV. (A near term goal will be to extend this range to include sub-kilovolt x-rays). The camera will utilize a front illuminated, virtual phase CCD made by Texas Instruments, Inc. The CCD has a 390 x 584 pixel array. Each pixel is 22 μ m square. The overall active detector area is 8.6mm x 12.8mm. The CCD will operate in a temperature range from -60°C to -100°C, and have an equivalent noise figure $\sim$ 10-20 electrons rms. (By comparison, a 1.5 keV x-ray deposits over 400 electrons in the CCD). The camera will be capable of single photon detection, and have a capability for non-dispersive energy discrimination. It will significantly enhance our ability for x-ray microscopy and spectroscopy using low brightness laboratory sources.

Acknowledgement

The development and implementation of new x-ray optical capabilities is a multi-disciplinary effort involving a variety of diverse technologies and disciplines in an interlocking collaboration. I am delighted to recognize the skilled contributions of colleagues and collaborators at institutions throughout the U.S. At IBM's T. J. Watson Research Center: D. P. Kern, T. H. P. Chang, and P. J. Coane; at MIT's Submicron Structures Laboratory: A. M. Hawryluk, M. Schattenburg, H. I. Smith, and J. Carter; at MIT's Center for Space Research: G. R. Ricker, J. Doty, J. Vellarga,

and G. Luppino; at Cornell University's NRRFSS: E. Wolf, R. Tiberio, B. Whitehead, and D. Costello; at University of Rochester's Laboratory for Laser Energetics: M. Richardson, D. Villeneuve and S. Letzring; at Purdue University: D. W. Sweeney; and finally at LLNL: G. Stone, G. Howe, R. L. Kauffman and H. Medeck.

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Figure Captions

Fig. 1-2: Simulation of the effects of nonlinear shadowgraph recording on the reconstruction of continuous x-ray source distributions. In (1) the coded aperture has 250 zones and the ZPCI Fresnel number is .074. In (2) the coded aperture has 250 zones and the ZPCI Fresnel number .342.

Fig. 3-4: Simulation of the effects of non-linear shadowgraph recording. In (3) the coded aperture has 100 zones and the ZPCI Fresnel number is .028. In (4) the coded aperture has 250 zones and the ZPCI Fresnel number is .045.

Fig. 5: Image data from the 100 keV x-ray point response test. (a) Coded image; (b) and (c) Reconstructed image data in seventh order.

Fig. 6: SEBL generated zone plate objective lens pattern. Minimum zone width is 1500Å; overall pattern diameter is 60 μm .

Fig. 7: SEBL generated zone plate condenser lens pattern. Minimum zone width is approximately 4500Å; overall pattern diameter is 0.8mm.

Fig. 8: Phase lens design scheme for silver. The energy bands for efficient operation extend from 110-180 eV and from 1.4-2.7 keV.

Fig. 9: SEM micrographs of the silver phase lens. The structure has 100 zones, a minimum zone width of 3200Å, and is 5500Å thick.

Fig. 10: A time resolved x-ray transmission grating spectrometer.

Fig. 11: A typical data set from the time resolved x-ray spectrometer. The x-ray emission is from a laser irradiated gold disk target illuminated at $3 \times 10^{14} \text{ W/cm}^2$ with $\lambda = 0.53 \mu\text{m}$ laser light.

Fig. 12: A schematic diagram of the x-ray imaging spectrometer. Typical data are shown for laser irradiated, gas filled, microsphere, laser fusion targets.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

(a)

1 mm
100 keV x-ray
coded image

100 keV x-ray
7th order

(b)

(c)

Fig. 5

Zone plate objective lens

$$D = 60 \mu\text{m}; N = 100; \Delta r = 1500 \text{ \AA}$$

IBM: T.J. Watson Res. Center
(D. Kern, T.H.P. Chang, P. Coane)

Zone plate condenser lens

Fig. 7

$$D = 0.8 \text{ mm}; N = 450; \Delta r \simeq 4500 \text{ \AA}$$

Cornell NRRFSS:
(E. Wolf, R. Tiberio, B Whitehead, D. Costello)

PHASE LENS DESIGN FOR SILVER: ENERGY BAND FOR EFFICIENT OPERATION

Only those energies where both η is small (here $\eta \leq 0.175$, $\epsilon_1 \geq 25\%$) and π is small (here $\pi \leq 1 \mu\text{m}$) are appropriate for phase lense operation. In the case of a silver phase lens one energy band for efficient operation extends from (110-180) eV and another from (1.4-2.7) keV

Fig. 8

40-01-0583-1756

X-RAY PHASE LENS: SILVER

X-ray phase lens for operation at $Al_{K\alpha} \simeq 1.5 \text{ keV}$

Fig. 9

TIME RESOLVED SOFT X-RAY SPECTROMETER: DEMONSTRATION

A free standing x-ray transmission grating is coupled with a soft x-ray streak camera to provide time resolved (~ 20 psec) continuous x-ray spectra over a broad spectral range (0.1-1.5 keV).

Shot No 31050709
40 30 0581 1207

TIME RESOLVED X-RAY SPECTRUM FROM LASER IRRADIATED GOLD DISK TARGET

Photographic data record

Source spectra at different times

Emission time history in separate energy bands

Fig. 11

Gold disk
 $3 \times 10^{14} \text{ W/cm}^2$; $\lambda = 0.53 \mu\text{m}$
 (=31082006)

IMAGING SPECTROSCOPY OF LASER IRRADIATED MICROBALLOONS

An x-ray transmission grating is coupled to a K-B Microscope to provide spectrally dispersed images of laser imploded microsphere targets

Fig. 12

DT filled glass microsphere
(#7529)

40-90-0982-2807A

Argon filled glass microsphere
(#7668)