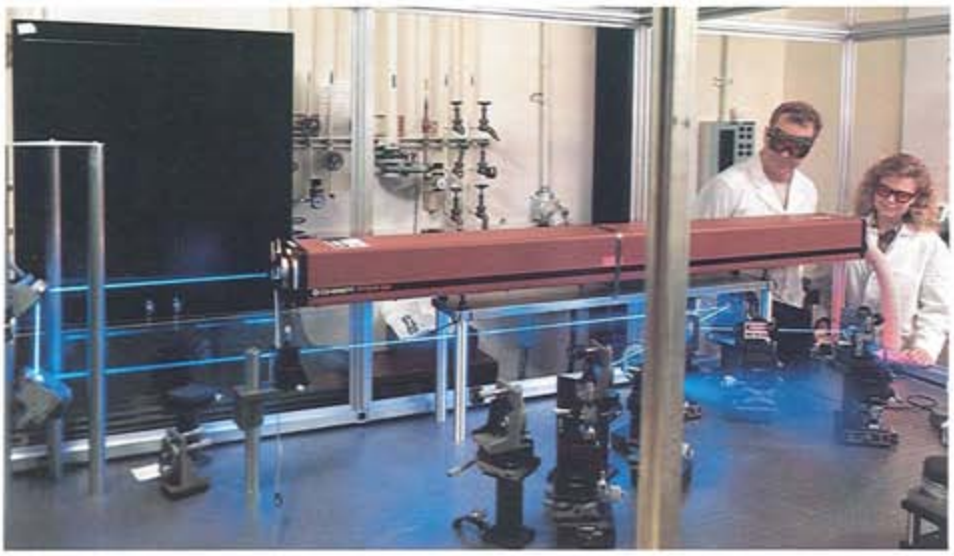

Technicians Bill Cook and Sherry Hill, in the Laser Program's Laboratory for Submicron Structures, are using the holographic lithography facility to fabricate periodic waveguide structures for soft x rays.

Emerging Applications

Several emerging applications could redefine the field of x-ray optics. They could have significant economic impact with implications for biotechnology, electronics and national security.

Beyond the relatively mature programs in x-ray laser cavities, x-ray microscopy, and x-ray holography, there are emerging new applications that could virtually redefine the field of x-ray optics. Here we explore four areas of particular promise:

- High-intensity x-ray lasers, which could create a new field of nonlinear x-ray optics.
- Soft-x-ray interferometry, which could extend the precision and scope of interferometric measurement significantly by reducing the wavelength by two orders of magnitude.
- Soft-x-ray waveguides, which could extend by two orders of magnitude the limits on practical guided wave devices.
- Soft-x-ray projection lithography, which could significantly affect the semiconductor electronics industry by establishing the viability of high-throughput x-ray lithography for the production of high-density (<100-nm linewidth) integrated circuits.

These efforts are currently in the very early stages of design or development, but all have the potential for considerable scientific and industrial payoff.

High-Intensity X-Ray Laser

A particularly interesting synthesis of the x-ray laser and x-ray optics technologies discussed in the previous sections would be the development of a high-intensity ($>10^{13}$-W/cm^2) soft-x-ray laser. At LLNL, we have been working on such a project with the goal of delivering an unprecedented intensity of narrowband soft x rays to a target. This would allow the controlled study of laser-matter interactions at specific x-ray wavelengths at intensities never before achieved in the laboratory. A corollary benefit of this effort could be the creation of a whole new field of nonlinear x-ray optics, just as nonlinear optics in the visible and infrared regions grew out of the development of high-intensity optical lasers in the 1960s.

Conceptually, the high-intensity x-ray laser would consist of a soft-x-ray gain medium within a double- or multipass cavity. The radiation emerging from the cavity would be imaged by a reduction lens (a Fresnel zone plate or a series of multilayer coated mirrors) to a small, high-intensity spot.

Preliminary Design

To illustrate the potential for such a system, we considered the following simple design. The gain medium of choice is the well-characterized neon-like strontium laser, 5 cm long and approximately 200 μm in diameter. The dominant line emission is at 16.41 nm. The measured small-signal gain is ~4.5 cm^{-1}, and the anticipated (i.e., calculated) saturation intensity is 2×10^{10} W/cm^2, which should be achieved with a gain-length product of ~15. In this design, the ASE is double-pass amplified using a normal-incidence spherical multilayer mirror placed 2 cm from the end of the gain medium. The mirror is assumed to have a reflectivity of 50% at 16.4 cm. The overall amplification length of the cavity is 10 cm, and the double-pass cavity length is 14 cm. For this application, the x-ray laser target

must be redesigned to provide a gain duration significantly greater than the 470 ps required for the double-pass transit of the cavity.

Under these conditions, the radiation emerging from the double-pass cavity will have an intensity I_L given by

$$I_L = I_{sat}\, g(L - l)\, R$$

$$\approx 3 \times 10^{11}\ \mathrm{W/cm^2}\ ,$$

where the saturation intensity $I_{sat} = 2 \times 10^{10}$ W/cm^2, the small-signal gain $g = 4.5$ cm^{-1}, the amplification length $L = 10$ cm, l is the saturation length (i.e., $g \times l = 15$), and the mirror reflectivity $R = 0.5$. The emerging radiation has a divergence $\Delta\theta$ given by

$$\Delta\theta = (d_L/L_0) = 1.4 \times 10^{-3}\ \mathrm{rad}\ ,$$

where the diameter of laser gain medium $d_L = 200$ μm and the cavity length $L_0 = 14$ cm, or equivalently a solid angle of

$$d\Omega \approx 2 \times 10^{-6}\ \mathrm{sr}\ .$$

The laser output beam (3×10^{11} W/cm^2, over a 200-μm diam, with 2×10^{-6} sr divergence solid angle) is imaged by an appropriate reduction camera of f/number $f\#$ to a spot size d, where

$$d = d_L\, f\#\, \Delta\theta\ .$$

For example, if $f\# = 7$, then $d = 2$ μm and the focused intensity is

$$I_{focus} \approx 3 \times 10^{14}\ \mathrm{W/cm^2}\ .$$

This value presumes a 10% first-order diffraction efficiency for the reduction lens. It does not account for a possible fill-factor loss (i.e., lens diameter smaller than beam diameter, a small effect) or possible reduction lens damage.

If one were to presume a reduction lens with $f\# = 2$, then the focused spot diameter would be reduced to $d \approx 0.6$ μm and the focused intensity would be

$$I_{focus} \approx 3 \times 10^{15}\ \mathrm{W/cm^2}\ ,$$

again accounting for lens efficiency but not for fill factor loss or possible lens damage.

The values shown here represent a preliminary design, simply to illustrate the potential of the x-ray laser and optics technologies that are presently available. In the course of development, different design choices may well be required, and an actual first-generation system may differ from the above design goals by one or two orders of magnitude. Nevertheless, it is clear that the technology is at hand for the development of high-intensity x-ray lasers that could parallel the development of high-intensity optical lasers in the 1960s and 1970s.

Applications

At this stage, it is difficult to make a reliable assessment of specific applications of the high-intensity laser. However, one need only recognize how high-intensity optical lasers have altered the scientific and technological landscape to appreciate the potential of such a capability at soft-x-ray wavelengths.

An area of application of particular interest is the generation and study of nonlinear x-ray optical phenomena driven by the large, high-frequency electric fields that the high-intensity laser could bring to bear on plasma or solid targets. For example, rough estimates of third-harmonic generation in an appropriately engineered plasma indicate that at 10^{14} W/cm^2, perhaps a 1% conversion efficiency to the third harmonic (e.g., 16.41 nm to 5.47 nm) could be achieved. Although such early estimates may appear naive in the years to come, the long-term potential of this technology is evident even now.

Soft-X-Ray Interferometry

The availability of high-quality x-ray mirrors and beamsplitters as well as high-brightness x-ray sources bodes well for the development of interferometry as a diagnostic tool at soft-x-ray wavelengths. Interferometry has been used at visible and near-ultraviolet wavelengths for the study of aerodynamics and fluid flow, plasma dynamics and atomic phenomena, as well as for high-frequency optical modulation and precision metrology. At hard-x-ray wavelengths, it has been used to study crystal structure and surface topography of solids. However, to date, no significant interferometry has been done at soft-x-ray wavelengths because of the lack of appropriate optics and sources. But as we have seen, the technological landscape has changed and the development of soft-x-ray interferometry is now possible.

The practical benefits of soft-x-ray interferometry will be broad and diverse. In the areas of temporal modulation and metrology, one may expect, at least in the long run, faster modulation and measurements of higher precision owing to the shorter wavelength of the radiation. In

addition, the greater penetration of soft x rays through gases and plasmas will provide the opportunity for precise interferometric characterization of such media in regions of parameter space (e.g., density, length) hitherto inaccessible. This capability is of particular interest to researchers involved in x-ray laser development. The diagnosis of high-density, large-scale plasmas will allow more detailed investigation of the hydrodynamics and population kinetics in x-ray laser gain media. These specific measurement opportunities are explored below.

Soft-x-ray interferometry will permit direct measurement of electron density profiles at well above the critical density for large-scale (~1-cm) x-ray laser plasmas. Such measurements have until now been impossible. In a high-density plasma with strong radial density gradients, the density-length product scales inversely as the square of the probe wavelength. That is,

$$\int_0^{L_p} n ds = (nL_p)_{max} \propto 1/\lambda^2,$$

where L_p is the length of the plasma, n is the plasma electron density, and λ is the wavelength of the interferometric probe. The shortest wavelength at which plasma interferometry has been successfully applied in the past is 266 nm. A decrease in probe wavelength to 13.1 nm (where there exist high-efficiency molybdenum/silicon multilayer optics and the neon-like molybdenum laser) would increase $(nL_p)_{max}$ by more than 400×. This would provide access to electron densities as high as 10^{22} electrons/cm^3 in an x-ray laser plasma 2 cm long.

Hook Interferometry

Another intriguing diagnostic possibility would be the use of Hook interferometry (i.e., interferometric spectroscopy) at soft-x-ray wavelengths for direct, time-resolved measurement of differential population densities of important transitions in x-ray laser plasmas. This could provide a detailed insight to the atomic kinetics of these complex plasmas and perhaps time-resolved observation of the creation of inverted populations in laser transitions.

Briefly, the Hook method uses an interferometer (typically a Mach Zehnder; see Figure 28) illuminated

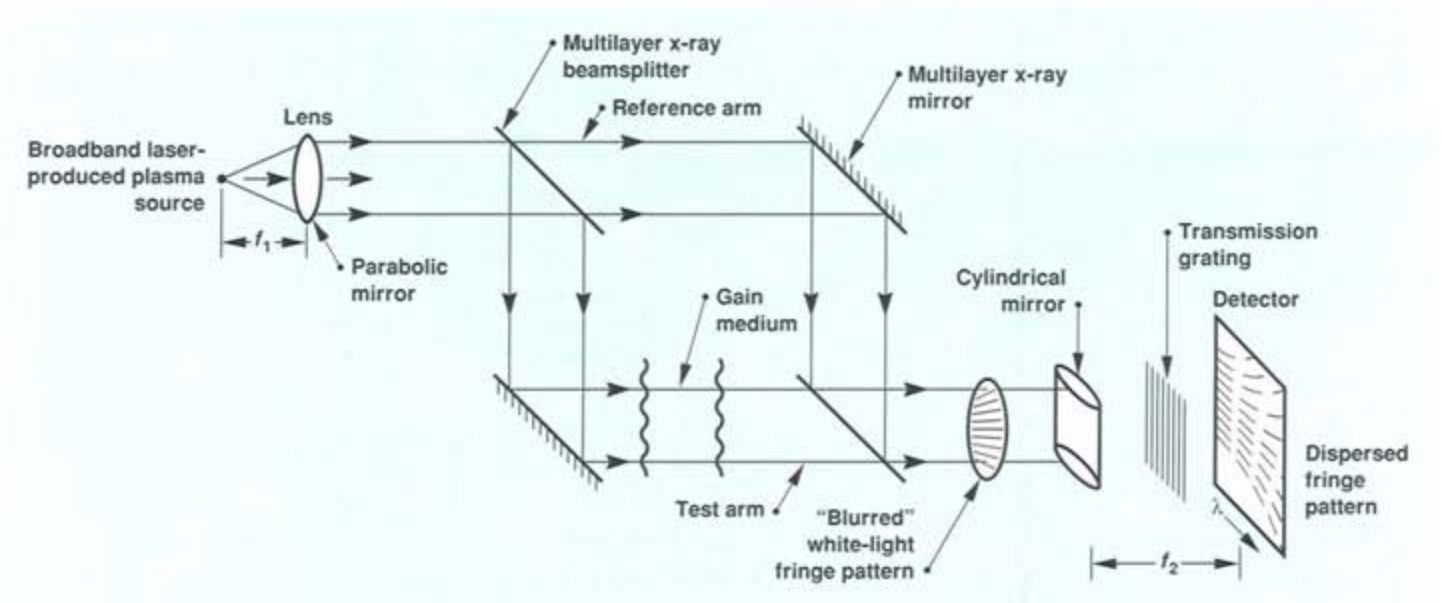

Figure 28. All the x-ray optical components needed to implement interferometry at soft x-ray wavelengths are now available. This could bring about a two-order-of-magnitude increase in interferometric measurement capabilities. Shown here is a schematic illustration of a design of a soft-x-ray Mach-Zehnder interferometer setup for Hook interferometry of an x-ray laser gain medium.

with collimated, broadband radiation. The resulting (blurred) fringe pattern is spectrally dispersed in an imaging spectrometer. The output (which can be displayed across the slit of a soft-x-ray streak camera for time resolution) is then simply a linear fringe pattern displayed vs wavelength. However, in regions of anomalous dispersion (i.e., at wavelengths near transitions), the fringes are not simply linear—in fact, they form sharp hook patterns. The separation between the hooks depends on the population difference of the transition and the oscillator strength, according to

$$\Delta_H \propto \left\{ \int_0^{L_p} N_{ij} f_{ij}\, ds \right\}^{1/2} ,$$

where N_{ij} is the population difference ($N_i - N_j$, in cm^{-3}) and f_{ij} is the oscillator strength for the transition at λ_{ij}.

The beauty of this technique lies in the fact that the key observable is the Hook separation Δ_H, a simple, linear distance on the detector. As a result, the technique does not require careful photometry or detector linearity (as does absorption spectroscopy). The Hook method is best suited for strong transitions (i.e., large f_{ij} for large Δ_H). It has a large dynamic range (since Δ_H is proportional to $N_{ij}^{1/2}$ and is not limited by the linear range of the detector), is insensitive to line shape variation, and can be used on optically thick transitions (since the technique measures phase shift away from line center).

Hook interferometry is a sophisticated technique, powerful in its ability to extract detailed spectroscopic information from high-density plasmas. However, for want of appropriate sources and optics, it has not yet been applied at x-ray wavelengths. Nonetheless, with the emergence of high-brightness, broadband sources of x rays (e.g., laser-produced plasmas), high-quality mirrors, beamsplitters, and imaging optics, as well as strong interest in the atomic kinetics of high-density, large-scale plasmas (e.g., x-ray laser gain media), all the elements are in place for Hook interferometry to become an important new diagnostic technique for high-density plasmas.

Soft-X-Ray Waveguides

The practical value of guided transmission of electromagnetic radiation has long been established. Indeed, at microwave, infrared, and optical wavelengths, considerable effort has gone into the development and optimization of classical waveguide structures for a wide variety of applications. (As discussed here, a "classical waveguide" is a long, narrow structure within which electromagnetic wave propagation is not adequately represented by geometrical or ray optics. It is a structure for which $s/\lambda \gtrsim 1$ and $t/\lambda >> 1$, where λ is the wavelength being propagated, s is a characteristic transverse dimension of the waveguide, and t is its length.)

At soft-x-ray wavelengths, guided-wave phenomena have received considerably less attention because of the perceived difficulty of fabricating vacuum structures on the scale of x-ray wavelengths and anticipated propagation losses in thin-film waveguide structures. In fact, at x-ray wavelengths, the majority of guided-radiation research has been done on x-ray light pipes ($s >> \lambda$), relying on multiple internal reflections of hard (0.15-nm) x rays from the interior surfaces of macroscopic capillary tubes ($s \sim 10$–$100\ \mu m$).

Recently, we have challenged the conventional thinking about the viability of soft-x-ray guided-wave propagation by fabricating vacuum waveguide structures and explicitly demonstrating classical guided-wave propagation at wavelengths as short as 5 nm. We have also proposed the use of resonant multilayer coatings on the interior walls of x-ray vacuum waveguide structures to improve propagation efficiency. Such demonstrations and proposals would have been impossible—even unthinkable—a decade ago.

We conducted a series of waveguide demonstration experiments at BESSY in a region of parameter space heretofore unexplored for soft x rays, namely, $s/\lambda \sim 3$–20 for $\lambda \sim 5$–30 nm, with $t/\lambda \lesssim 140$. The synchrotron radiation incident upon the waveguide structure was narrowband ($\lambda/\Delta\lambda \sim 500$), linearly polarized (along the x direction in Figure 29), and collimated into a narrow beam (~200 μm in diameter with a 0.25-mrad divergence).

A typical waveguide structure is shown in Figure 30. It is a free-standing transmission grating (i.e., it has no substrate or support membrane) with a 300-nm grating period. The grating lines are gold and the spaces vacuum. In the experiment, the lines (and spaces) were aligned along the vertical (y direction in Figure 29) and were supported by a 6-μm-period orthogonal array of gold crossbars, (aligned along the x direction, but not shown in Figures 29 or 30). The use of a periodic waveguide structure simplified the problem of waveguide propagation measurements. For example, from the measured diffraction pattern, the amplitude and phase distribution of the waveguide-transmitted radiation could be inferred.

The experimental setup is illustrated in Figure 29. The synchrotron beam was incident along the $+z$ direction with its electric field polarized parallel to the x axis. At zero tilt angle, the grating's lines were aligned along y, its periodic variation along x, and its thickness along z. The grating tilt axis M passed through the grating and was parallel to the y axis. A channeltron detector, operating in the photon-counting mode, was used to measure the pattern of diffracted radiation emerging from the grating structure.

Results of Guided-Wave Propagation Experiments

In these experiments, the guided-wave propagation phenomena were illustrated by diffraction pattern asymmetries resulting from changes in the transmission grating tilt angle and/or the incident x-ray wavelength. The asymmetries arise from variations in the phase and amplitude distribution across the output channels of the transmission grating. These phase and amplitude variations are produced by changes in the propagating mode structure as the grating tilt angle and/or x-ray wavelength are changed.

The dependence of diffraction pattern asymmetry on grating tilt angle is illustrated in Figure 31. The data are for 20.8-nm radiation incident upon a transmission grating with line width of 100 nm, space width of 200 nm, grating period of 300 nm, and grating thickness of 470 nm. Plotted are values of relative diffraction efficiency into 0, ±1, ±2 orders for grating tilt angles varying from −6 to +6°. The measured values of diffraction efficiency presented in the data are determined primarily by the throughput of the grating support structure. For example, in the $\theta_T = 0$ data of Figure 31, we find that 42% of the x-ray energy incident upon the open grating channels appears in the 0, ±1, ±2 orders of the diffraction pattern.

These measured diffraction patterns show a distinct asymmetry, with energy preferentially directed into those orders toward which the grating is tilted. As the tilt angle is increased, the asymmetry of the diffraction pattern increases. This provides a degree of directional

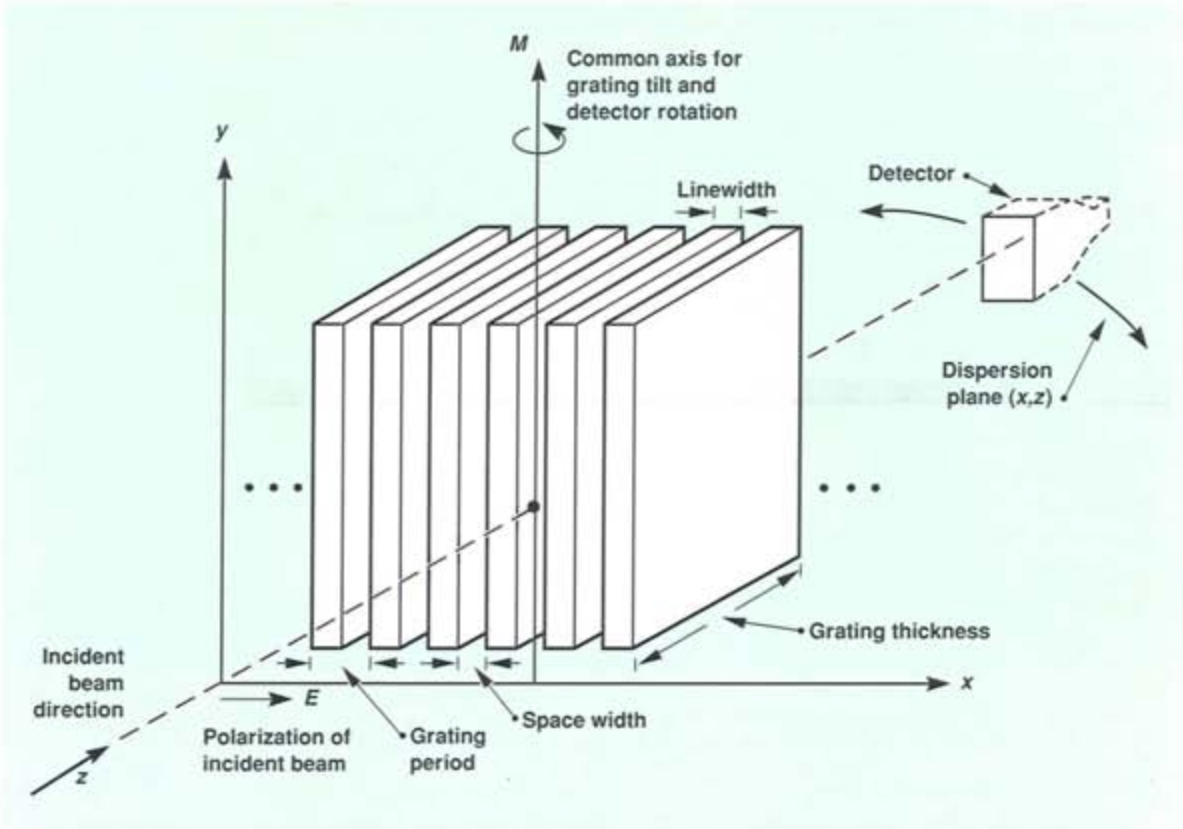

Figure 29. **Experimental setup of the LLNL experiments that provided the first demonstration of classical waveguide phenomena at soft-x-ray wavelengths.**

control over the diffracted x-ray energy, somewhat analogous to the directional control of a radar using a phased array of sources. In this case, the sources are the output channels of the transmission grating, and their amplitude and phase distributions are determined by the propagation characteristics of the waveguide channels.

Figure 32 illustrates the transmission of the soft-x-ray radiation through the waveguide channels at extreme tilt angles (angles for which the beam had no simple geometric line of sight through the waveguide structure). Radiation at 30 nm was incident upon the grating structure of Figure 30 at tilt angles of 6, 12, and 18°. The cutoff tilt angle for the geometric line of sight through this grating was ~8°. As noted above, the diffraction pattern asymmetry continued to increase and diffraction efficiency continued to decrease with increasing tilt angle, but there was no sharp change in waveguide propagation characteristics beyond the geometric cutoff angle.

Fabrication Challenges

If this x-ray guided-wave technology is to play an effective role in practical applications involving the manipulation and transport of soft x rays, waveguide propagation efficiency must be significantly improved. This will require the fabrication of precision vacuum waveguide structures with carefully controlled dimensions and (x-ray) optically smooth walls. In addition, the waveguide design must minimize wall losses by restricting the guided fields to the vacuum

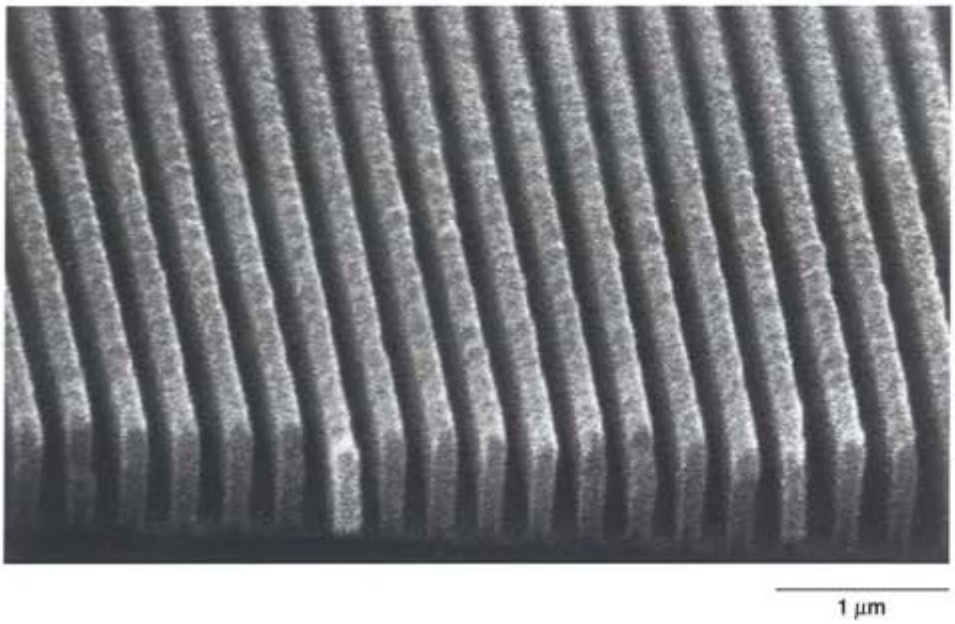

Figure 30. Nanolithographic techniques have been used to fabricate 100-nm-scale soft-x-ray waveguide structures. A periodic gold waveguide structure is shown here. When used in experiments, the waveguide structure is free standing (i.e., it has no substrate). It is supported only by an orthogonal array of gold cross bars (not shown).

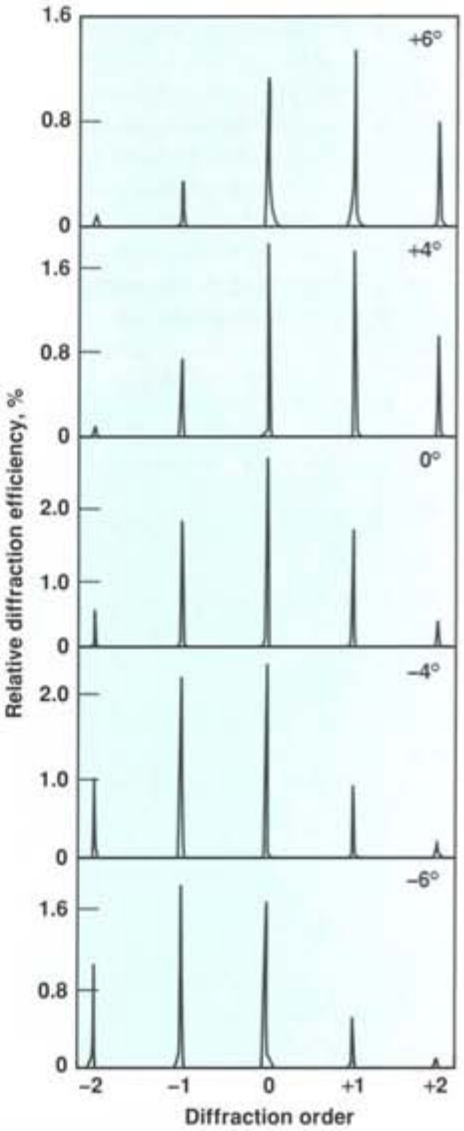

Figure 31. Classical waveguide propagation is inferred from the asymmetric diffraction patterns produced by the radiation emerging from the periodic waveguide structure. Shown here are measured diffraction patterns (at λ = 20.8 nm) at a variety of tilt angles (θ_T) from a waveguide having 100-nm lines, 200-nm spaces, and a total propagation length of 470 nm.

region of the structure. It appears that the technology may exist already to meet both these requirements. We have proposed fabricating high-precision waveguide channels using well-established techniques for anisotropic etching of silicon. Such an anisotropically etched pattern is shown in Figure 33. Since pattern geometry and dimensions are determined by the crystal structure of the silicon, pattern dimensions can be precisely controlled and the walls can, in principle, be made atomically smooth.

Reducing waveguide wall losses requires the fabrication of the x-ray analog of "perfectly conducting" waveguides (i.e., reflecting walls). This can be achieved using resonant multilayer coatings on the interior walls of the anisotropically etched vacuum waveguide structures. In addition to significantly reducing propagation losses, the multilayer walls, being resonant, will aid in selection and propagation of single transverse modes. Possible waveguide geometries using multilayer coated, anisotropically etched patterns in silicon are illustrated in Figure 34. We are now fabricating and testing such waveguide structures.

Soft-X-Ray Projection Lithography

In the early 1970s, it was presumed that x-ray lithography would be the long-term technology of choice for the replication of high-density integrated circuits, once the technical details (source, mask, etc.) were worked out. It was expected that the transition to significantly shorter wavelengths would ensure higher-resolution pattern replication than would be possible with optical lithography.

What was overlooked at the time was the significant advantage that accrued to optical lithography from the advanced state of optics at visible and near-ultraviolet wavelengths. Optical lithography, using low-f/number imaging systems, could achieve a resolution approaching the

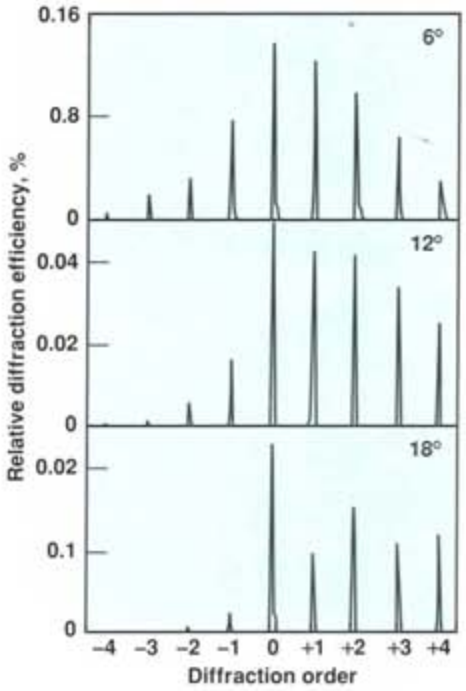

Figure 32. The presence of classical waveguide propagation is illustrated by efficient radiation transmission through the structures at extreme tilt angles (θ_T) where there is no direct line of sight through the waveguide channels. This is illustrated here at $\lambda = 30$ nm for a waveguide tilted at 6°, 12°, and 18°. The geometric line of sight through the structure was cut off at $\theta_T = 8°$. There is no precipitous change in waveguide propagation characteristics as the cut-off angle is exceeded.

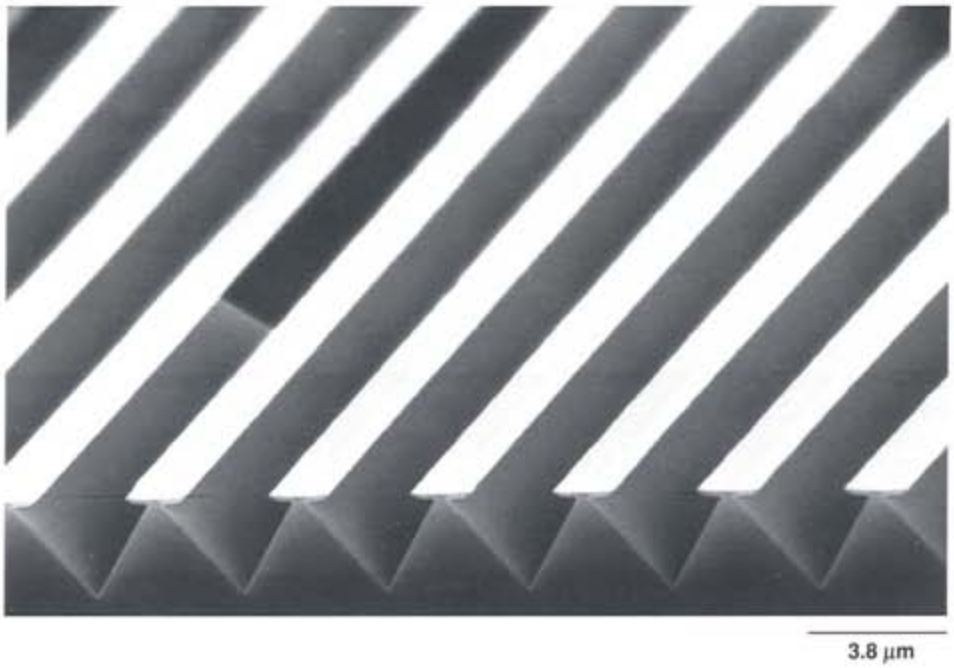

Figure 33. An example of an anisotropically etched periodic sawtooth pattern in silicon. Anisotropic etch technology has been proposed for the fabrication of advanced soft-x-ray waveguide structures .

wavelength of the working light, whereas proximity print x-ray lithography (PPXRL), being without optics, could not take full advantage of the wavelength scaling to x rays.

The resolution of PPXRL is limited by practical mechanical considerations (such as the mask-to-wafer gap) to a resolution of ~0.2–0.5 μm. Optical step-and-repeat cameras, on the other hand, have already achieved a 0.5-μm resolution, and it is anticipated that 0.25-μm resolution may be achieved using argon-fluoride excimer laser illumination at 193 nm. Given this perspective, one can readily understand the paralysis of industrial decision makers and their desire for the government and other industrial partners to share the cost of the questionable venture into x-ray lithography (see "The Dilemma ..." p. 48).

Recently, LLNL researchers have proposed rethinking the x-ray lithography dilemma by introducing x-ray optical components—specifically, by using a multilayer soft-x-ray reduction camera for lithographic replication of high-density integrated-circuit patterns. Although this suggestion is not entirely new, it is timely and could serve to redefine the question of x-ray vs optical lithography. In particular, if diffraction-limited optics could be achieved at soft-x-ray wavelengths, then the true advantage of wavelength scaling would be realized in x-ray lithography. The resolution limits of x-ray lithography would be determined not by mechanical considerations but by the x-ray wavelength and the f/number of the optics (and ultimately by other phenomena, such as the resolution of the resist).

One can thus envision a follow-on technology to PPXRL that would allow x-ray lithographic replication at a resolution well below 0.2 μm. This would provide a clear advantage for x-ray lithography over optical lithography, making the industrial choices much easier. Here we provide a brief discussion of both proximity print (i.e., PPXRL) and projection print (i.e., using reduction optics) x-ray lithography, highlighting their advantages, difficulties, and technical challenges.

Proximity-Print Process

X-ray lithography, as first proposed in 1972 by Spears and

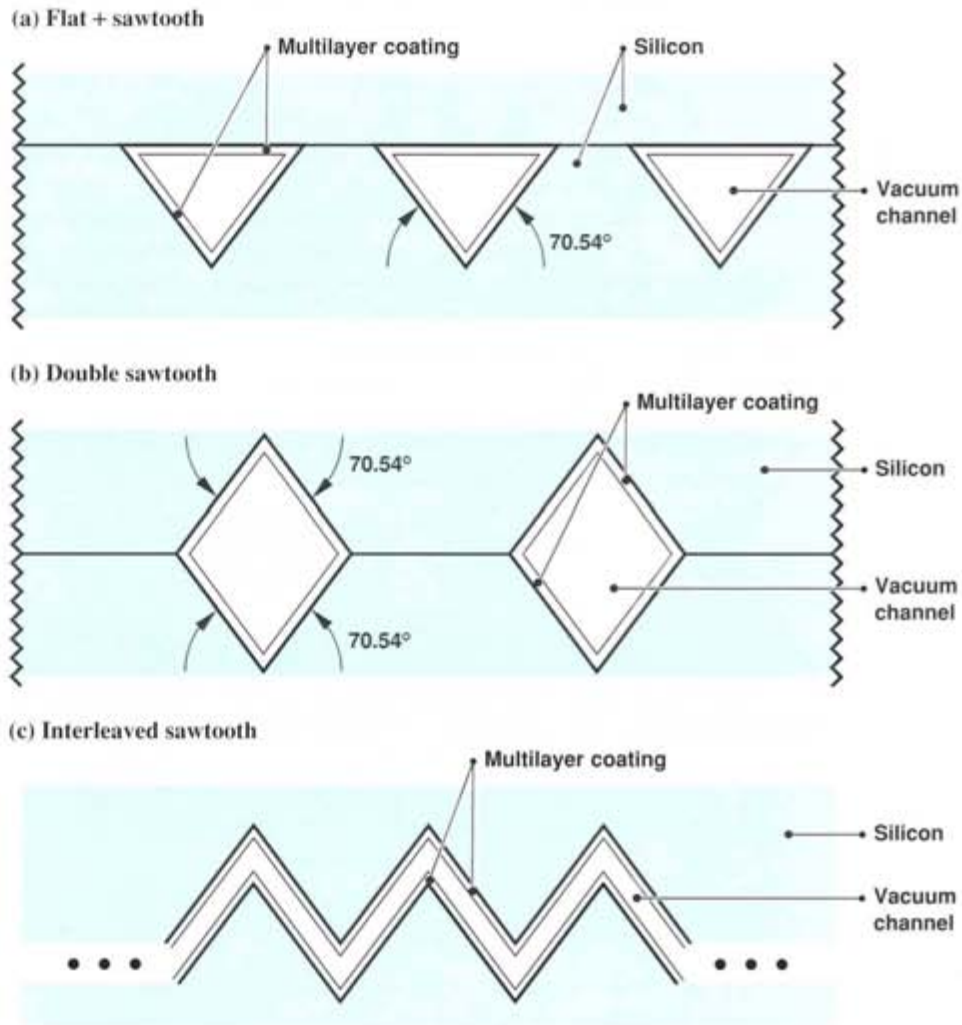

Figure 34. Simple ideas for the possible fabrication of multilayer-coated, periodic waveguide structures using the anisotropic etch technology illustrated in Figure 33. These designs require the application of multilayer coatings onto anisotropically etched sawtooth structures in silicon.

Smith and as generally understood in the published literature, is the proximity print process described in the paragraphs above. PPXRL is a one-to-one shadow print process. Damage to the mask from contact with the wafer is prevented by a small mask-wafer (proximity) gap (~50 μm). As currently conceived, PPXRL would use highly collimated synchrotron radiation in a bandwidth between 0.2–5 nm. As the x-ray analog of optical "contact" lithography, PPXRL has a number of advantages:

- Better resolution (perhaps down to 0.2 μm, depending on the engineering details of its implementation) because of the shorter wavelength.
- The use of a single-layer resist technology, since the soft-x-ray absorption depth in the resist is greater than the required resist thickness.
- Significantly lower sensitivity to particle and dust contamination, because of greater penetration and negligible scattering of x rays.
- Large depth of focus (>10 μm), arising from the collimation of the synchrotron radiation.

All these advantages combine to provide PPXRL with the potential for a very high-throughput in high-density integrated circuit production.

However, PPXRL is not without its limitations and difficulties. The key problem is in the proximity print x-ray mask. By necessity, the PPXRL mask consists of a very thin (~1-μm) support membrane of low-Z material carrying a high-aspect-ratio, high-Z absorber pattern. As a result, x-ray masks are fragile (requiring an appreciable proximity gap), are subject to problems of stability and radiation damage, have much lower contrast, and are more difficult to fabricate than optical masks. In addition, since PPXRL is a one-to-one replication process, it requires a high-resolution mask technology, which significantly increases the cost of mask fabrication. PPXRL also requires a very costly (e.g., synchrotron source.

The practical limits to PPXRL resolution arise from Fresnel diffraction blurring due to the finite mask-wafer gap and from the relatively low contrast of the x-ray masks. Thus the PPXRL resolution limit is estimated to be ~200 nm. This resolution is not much better than that expected from "optical" lithography using excimer lasers and new hybrid-optics reduction cameras. "Optical" lithography uses a much simpler and less expensive mask technology and does not require an expensive source.

The Dilemma over X-Ray Lithography

"Electronics executives and scientists are warning that the Japanese are rapidly pulling ahead of the United States in development of a crucial x-ray technology that will be used to manufacture computer chips in the mid-1990s. ... The developing technology called x-ray lithography can make 'denser' chips that ... will ultimately be able to store a thousand times more data. ... The experts are urging the creation of a national research program to insure that American manufacturers are not shut out of the world semiconductor market. The technology is considered too expensive for companies to develop alone. Indeed, ... officials at IBM have approached some American chip makers and offered to share costly equipment for IBM's x-ray technology research. 'Investment in this vital technology is not a matter of choice, and it must happen soon,' said Jack D. Kuehler, IBM vice chairman. ..."

New York Times, *12 December 1988*

The near-term technological choices for the future of high-resolution lithography are fraught with controversy. American industry has anguished for a decade over the decision to make the transition from optical to x-ray lithography. Retooling will cost billions of dollars and will require a revolutionary change in semiconductor production technology. Even more important is that proximity-print x-ray lithography (PPXRL)—the logical first-generation choice for an x-ray lithographic technology—continues to be plagued by technical uncertainties, while optical lithography continues to improve and narrow the perceived advantage that PPXRL might have. In the meantime, Japanese industry, with its strong unified capital base, is heavily invested in exploiting PPXRL. Thus, American semiconductor manufacturers are faced with a dilemma: Should an individual company invest a billion dollars in retooling for a technology with an uncertain future, or should it wait until the choices are clear and risk being overtaken by advanced Japanese production technology in an industry vital to national security and industrial competitiveness?

Projection X-Ray Lithography

Projection x-ray lithography (PXRL) is the x-ray analog of modern optical lithography using sophisticated reduction optics to project a diffraction-limited demagnified image of an integrated-circuit mask onto a semiconductor wafer. If successful, a PXRL system would retain many of the conveniences of optical lithography while incorporating the advantages of operating at x-ray wavelengths.

One such PXRL system is illustrated in Figure 35. Briefly, it uses a multilayer-coated Schwarzschild x-ray reduction optic to project a reduced image of an x-ray reflecting mask onto a resist-coated wafer. This system calls for multilayer coated spherical mirrors and a reflecting x-ray mask, which is an integrated circuit pattern atop a multilayer mirror. The novel x-ray mask design is a direct outgrowth of the holographic optical-component technology discussed earlier. This system would operate at 13 nm and have a diffraction-limited resolution of ~100 nm. It would require a synchrotron beamline with an insertion device or a high-power, laser-driven, x-ray source for high throughput.

The importance of our soft-x-ray projection lithography concept goes beyond the details of any specific design. By incorporating diffraction-limited x-ray optics into the overall scheme of x-ray lithography, it avoids the three major problems of PPXRL. (1) With the incorporation of an x-ray reduction camera, x-ray lithography would no longer be a one-to-one replication process. This could eliminate the need for a submicrometer mask technology. (2) A reflecting x-ray mask would be more robust and would have higher contrast than a transmission mask. (3) The ultimate resolution of the system would be the product of the x-ray wavelength and the f/number of the imaging system ($\lambda f\#$), allowing for significant linewidth reduction as the technology progressed.

The extraordinary potential of projection x-ray lithography is exceeded perhaps only by the staggering technological challenge it presents. A number of new x-ray-optics capabilities will have to be developed, including:

- More efficient multilayer mirrors.
- High-contrast, defect-free multilayer reflection masks.
- Diffraction-limited, multilayer, spherical x-ray mirrors.
- Precision test facilities for characterizing the imaging performance of the multilayer-coated optics.
- An appropriate synchrotron or laser-driven x-ray source.

In addition, significant engineering innovations will be required to address the problems of alignment (mirrors as well as mask registration), system metrology (positions of mirror, mask, wafer, etc.), and feedback control. All of these problems are inherent in a high-speed, high-throughput, production-line facility.

Projection x-ray lithography, as a follow-on technology to PPXRL, is under serious consideration as a research and development effort at LLNL and other research institutions. This is compelling evidence for the ongoing revolution in x-ray optics, since only in a period of such extraordinarily rapid progress and optimism about the future could so challenging a proposal appear so reasonable.

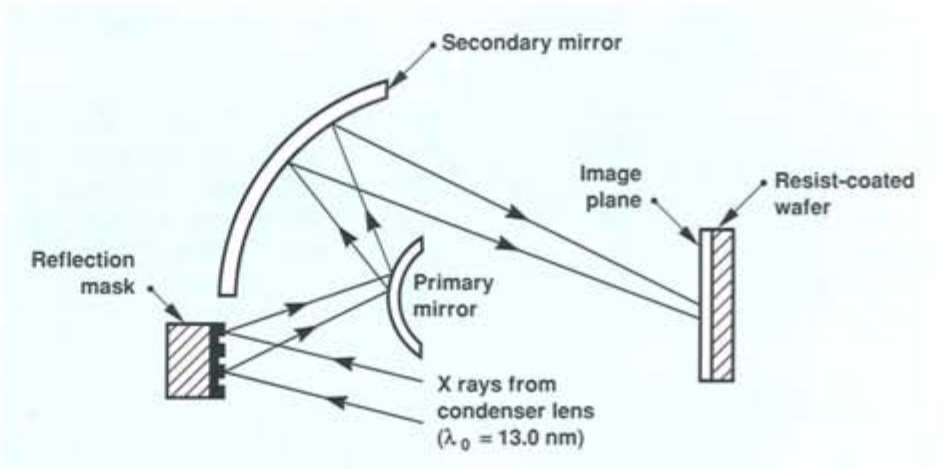

Figure 35. A possible projection x-ray lithography system utilizing a reflecting multilayer x-ray mask and a pair of multilayer, coated spherical mirrors for high-resolution imaging optics. As an advanced technology, x-ray lithographic projection would allow industry to benefit fully from the resolution advantages of operating at shorter wavelengths.

Developers of the x-ray beamsplitters: (left to right) Andrew Hawryluk, Nat Ceglio, Troy Barbee, and Daniel Stearns. The group of LLNL researchers posed for this photograph in the summer of 1987 after learning that their work had won an R&D100 award.

Future Directions

The prospects are bright for continued advances in x-ray optics. However, to achieve the real payoff—the major, unanticipated breakthroughs that reshape scientific thinking—we must maintain the exciting, creative culture underlying the 1980s revolution in x-ray optics.

The most mysterious aspect of difficult science is the way it is done. Not the routine, not just the fitting together of things that no one had guessed at fitting, not the making of connections; these are merely the workaday details, the methods of operating. They are interesting, but not as fascinating as the central mystery, which is that we do it at all, and that we do it under such compulsion.

Scientists at work have the look of creatures following genetic instructions; they seem to be under the influence of a deeply placed human instinct. They are, despite their efforts at dignity, rather like young animals engaged in savage play. When they are near to an answer their hair stands on end, they sweat, they are awash in their own adrenaline. To grab the answer, and grab it first, is for them a more powerful drive than feeding or breeding or protecting themselves against the elements.

It sometimes looks like a lonely activity, but it is as much the opposite of lonely as human behavior can be. There is nothing so social, so communal, so interdependent. An active field of science is like an immense intellectual anthill; the individual almost vanishes into the mass of minds tumbling over each other, carrying information from place to place, passing it around at the speed of light. ... It is the most powerful and productive of the things human beings have learned to do together in many centuries, more effective than farming, or hunting and fishing, or building cathedrals, or making money.

It is instinctive behavior, in my view, and I do not understand how it works. It cannot be lined up in tidy rows and given directions from printed sheets. You cannot get it done by instructing each mind to make this or that piece, for central committees to fit with the pieces made by other instructed minds. It does not work this way.

What it needs is for the air to be made right. If you want a bee to make honey, you do not issue protocols on solar navigation or carbohydrate chemistry, you put it together with other bees and you do what you can to arrange the general environment around the hive. If the air is right, the science will come in its own season, like pure honey."

adapted from
Lewis Thomas, *Lives of a Cell*

Predicting the course of technological change is a very difficult business. In a field like x-ray optics, which is undergoing the most exciting and creative period in its history, the constantly changing technological landscape makes accurate prediction of the future highly unlikely. Under such circumstances, conventional wisdom reduces to "predicting the

predictable"—that is, presuming that the major research projects currently under way will make timely progress. Under such circumstances, we might expect the following technological capabilities in the 1990s:

- X-ray lasers operating in the "water window" at or below 4.4 nm, making possible x-ray microscopy of living cells.
- Efficient normal-incidence x-ray mirrors and beamsplitters operating at or below 4.4 nm. These could be used for x-ray laser cavities, interferometry, and even projection lithography at these shorter wavelengths.
- An increase in the number and efficiency of extreme-ultraviolet lasers operating at wavelengths below 100 nm, as we better understand the kinetics of extreme ultraviolet systems.
- High-intensity, soft-x-ray lasers operating at focused intensities of 10^{12} to 10^{15} W/cm^2, with the subsequent creation of a whole new field of "nonlinear x-ray optics," as challenging and productive as the field of nonlinear optics created by high-intensity optical lasers.
- Smaller (perhaps table-top), more efficient, soft-x-ray laser systems.
- X-ray holography of live cells with a spatial resolution less than 50 nm.
- X-ray microscopy of live cells with a spatial resolution less than 10 nm.

It will be interesting to look for announcement of these "breakthroughs" over the next decade. They will represent a great boon for x-ray technology.

However, even more interesting than the "*predictable*" will be the "*unpredictable*": the possibility that these new capabilities will spawn other revolutions in physics, microbiology, and related fields. Perhaps the high-resolution, real-time x-ray images of living cells will completely change our thinking about cellular function and thereby lead to new strategies for disease prevention and control. Or perhaps unexpected results from the interaction of extremely high-intensity x-ray laser light with matter will force us to rethink our understanding of the quantum world. These "*new piece(s) of truth about nature*" will be the hallmark of a truly successful revolution in x-ray optics.

In the midst our optimism, however, we must remember that revolutions can and do fail. Failure can result from a lack of interest or, as is more likely in this case, from well-meaning efforts to focus the creative, apparently chaotic activity into narrowly defined "useful" channels. ("*It cannot be lined up in tidy rows. ... It does not work this way.*") At greatest risk, under these circumstances, are not the predictable items listed above. They would likely—at least in part—still be accomplished, even if more slowly.

The Revolution Continues ...

During the past few months, a number of significant advances in x-ray optics have been announced, providing evidence that the pace of progress shows no sign of slowing:

- Dennis Matthews, Brian MacGowan, and the LLNL x-ray laser team announced the production of amplified spontaneous emission at 4.48 nm in nickel-like tantalum. These results are a significant step toward the ultimate achievement of an x-ray laser source for holographic microscopy of live cells.
- Szymon Suckewer and the Princeton x-ray laser team announced a table-top x-ray laser at 18.2 nm. This x-ray laser is pumped by a small, 6-J neodymium:glass laser.
- In soft-x-ray projection lithography:
  - The x-ray optics group at LLNL announced the fabrication and test of the first reflection x-ray mask for projection lithography.
  - An x-ray imaging team at AT&T achieved the first high-resolution (~200-nm) lithographic reproductions using an extreme-ultraviolet reduction camera operating at 40 nm.
  - Two x-ray imaging teams (one from AT&T, another from Lawrence Berkeley Laboratory/University of Wisconsin) are currently testing soft-x-ray reduction cameras for high-resolution replication of integrated circuit patterns. These cameras are designed to operate at ~13 nm with a nominal resolution of 100 nm.

Instead, the loss will be in the unpredictable, creative, major breakthroughs that never happen. They are on no list—their specific loss cannot be documented.

For the most promising and productive future, the hope is that, amidst the growing interest and appreciation of x-ray optics, the creative and competitive culture that exists among the many diverse research groups around the world will be maintained; that those who control the field will resist the temptation to structure it too rigidly in the name of enhanced productivity in narrowly defined areas of application. Most needed is an enlightened interest, the wisdom, to *"make the air right,"* and the patience to allow *"the science to come in its own season, like pure honey."*

Key Words: soft-x-ray interferometry; soft-x-ray waveguides; synchrotron insertion devices; x-ray holography; x-ray lasers; x-ray lithography; x-ray optics—Fresnel lenses, multilayer mirrors; x-ray microscopy.

Notes and References

1. The refractive term may be written as

$$\mu = \left(1 - \frac{2k - k^2}{\sin^2\theta}\right)^{1/2},$$

where the complex refractive index is

$$n = 1 - k + i\beta,$$

and θ is the measured Bragg angle. (See T. W. Barbee, *Opt. Eng.* **25**, 898 (August 1986).

2. The condition $w << (\lambda q)^{1/2}$ assures that the size of the recorded hologram is much larger than the object, so that in image reconstruction the local image intensity will be greater than the background intensity. This is a common requirement in holography and pseudo-holography (coded imaging). It is sometimes referred to as the condition of large "information compression." For a more detailed discussion, see N. M. Ceglio and D. W. Sweeney, in *Progress in Optics*, E. Wolf, Ed. (North Holland Publishing, Amsterdam, 1984), Vol. XXI, p. 286.
3. Detailed inspection of the holographic fringe pattern indicates visible, well-defined fringes out to a numerical aperture, $\sin\theta \sim 1/25$. Using $\delta = 0.61\ (\lambda/\sin\theta)$, a precise form of the diffraction-limited resolution, implies that a transverse structure down to a resolution less than 40 nm was recorded in the resist pattern. For further discussion, see M. Howells et al., *Science* **238**, 514 (1987).
4. Note that there is some controversy concerning the scaling of specimen dose with image resolution. Howells presents the scaling as δ^{-6}, whereas London, Trebes, et al., claim a δ^{-4} scaling.
5. Holography does offer the potential of three-dimensional imaging. However, the limited longitudinal resolution, $\Delta \sim \lambda/\theta^2$, and the competition with microtomography by multiple projections leaves unresolved the issue of just how much an advantage this is for holography.

Note: Extensive bibliographic references are contained in N. M. Ceglio, "Revolution in X-Ray Optics," *J. X-Ray Sci. Technol.* **1**, 7–78 (1989).

Abstract

Revolution in X-Ray Optics

The past half-decade has witnessed a technological revolution in our ability to generate, control, manipulate, focus, and detect x rays. The emergence of x-ray lasers and synchrotron insertion devices has increased the brightness of laboratory x-ray sources eight to twelve orders of magnitude. Also, significant advances have occurred in the development of normal-incidence x-ray mirrors and beamsplitters, diffraction-limited x-ray lenses, x-ray microscopy, x-ray holography, x-ray waveguides, and CCD x-ray detector arrays. Using these new capabilities, researchers are taking the first steps toward developing sophisticated soft-x-ray optical systems, including soft-x-ray interferometers, high-intensity x-ray lasers, and projection optics for x-ray lithography. An overview of these developments is presented and the question addressed: Why is this happening now?

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