Laser-produced x-rays for compact x-ray lithography and microscopy

Harry Rieger

A high-brightness, high-power, diode-pumped laser system generates soft x-rays for practical applications.

Synchrotrons provide a very wide photon radiation spectrum that includes high-power soft x-rays (1–4nm). However, synchrotron facilities are very large and expensive, require dedicated staff to operate, and are time-shared by many users. Laser-produced x-ray (LPX) technology provides an inexpensive alternative soft x-ray source. The equipment is small (the size of a bench or cabinet), portable, and affordable. Even small companies can acquire it as part of their operation.

The concept of LPX is to focus a high-brightness laser beam onto a target, thereby generating extremely hot plasma that also emits in the soft x-ray region (down to $\sim 0.8$nm). Laser brightness in the order of $10^{14}$W/cm$^2$ on target is needed for generating x-rays, and practical applications such as lithography and microscopy require high average power.

A tabletop LPX source consists of two major subsystems: a high-brightness, high-power, diode-pumped neodymium-doped yttrium-aluminum-garnet (Nd:YAG) laser system, and a target chamber that contains a moving tape target. The laser system is composed of a single master oscillator (MO), followed by a pre-amplifier (pre-amp), and one or more parallel amplifiers. The MO generates the short pulse duration with near diffraction-limited (DL) beam quality. For good laser energy extraction from the amplifiers, a pre-amp is used to boost the beam energy out of the MO. Figure 1 shows a 300W laser where a single pre-amp drives four parallel amplifiers. The pre-amp beam splits four ways to feed four parallel amplifiers. Similar to the pre-amp, the amplifiers are also configured in a passive four-pass amplification scheme. Each amplifier consists of two Nd:YAG laser heads that are transversely pumped. The amplifier goes into saturation for good laser energy extraction. Slight degradation of beam quality is a result of hard aperturing in the laser rods.

The laser heads are designed to achieve efficient and uniform energy deposition in the Nd:YAG rods. Each amplifier emits a stream of 250mJ/pulse, 700ps pulses (due to gain narrowing) at a repetition rate of 300Hz for an average power of 75W and with $1.5\times$DL beam quality.

Figure 2 shows the near-field beam profiles of the MO, pre-amp, and amplifier. The MO has a perfect TEM00 profile, while the pre-amp has a slight flattening of the top. The ring pattern

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of the amplifier beam profile is due to the hard aperturing of the laser rod. It was necessary to overfill the amplifier aperture for maximum extraction of laser energy. However, measurements of the amplifier’s far field resulted in $\sim 1.5 \times DL$ beam quality. Figure 3 shows temporal traces of the laser pulse using a 2ps-resolution streak camera and a 2GS/s oscilloscope.

The laser accommodates target material in several forms and shapes from moving solid to gas jet. In our case, the preferred target is a solid tape. A solid target does not require a high-vacuum chamber, and the tape form allows most of the debris to go to the back side (opposite the laser and x-ray emission side) for long runs, without replacing target material. The only drawback of solid target material is forward debris. Debris mitigation schemes such as gas flow, electrostatic repulsion, and magnetic diversion can minimize debris significantly but not eliminate it. We developed a mechanical shutter that can discriminate between x-ray velocity (speed of light) and debris velocity.

We showed experimentally that no debris with initial velocity of over $10^6 \text{cm/s}$ is found. The shutter wheel triggers the laser with the appropriate delay to obtain 100% x-ray throughput. Small clusters of ablated target material are suspended in the chamber ambient helium gas. A gentle laminar closed helium flow through a fine particulate filter removes all the suspended debris.

**X-ray lithography**

For x-ray lithography, x-ray generation takes place when the laser beams are focused onto a copper (Cu) tape target (see Figure 4). A simple two-reel mechanism drives the thin copper tape, and the velocity of the tape is sufficient to introduce a fresh copper surface for every new laser pulse. A single laser beam from the four-beam system yields $\sim 3W$ of x-ray power into $2\pi sr$ ($\sim 4\%$ conversion efficiency). Spatial

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Figure 6. This SEM image shows exposed photoresist using LPX with feature sizes down to 70nm.

Figure 7. This 85μm-diameter zone plate serves as a positive lens for x-rays.

Figure 8. Panel (a) shows the x-ray microscope at WonKwang University in Korea. The laser system is seen at bottom left. Panel (b) shows a narrow spectrum, $\lambda/\Delta = 1000$, and panel (c) gold mesh imaged at 45nm resolution.

and temporal overlaps of the outputs from all four amplifiers at the target location yield 9% conversion efficiency. The system generated average x-ray power of over 24W into $2\pi sr$, with an effective lithographic wavelength of 11Å.

In proximity x-ray lithography, the mask is placed very close to the wafer, and the shadow of the mask prints the features on the photoresist; therefore, the spectral content of the x-ray is not critical. Figure 5 shows a typical x-ray spectrum generated by our LPX system. The complete x-ray source is very compact and has the potential to be reliable and robust. Lithographic exposures were made using the our LPX.3 Figure 6 shows an SEM image of exposed resist with feature sizes down to 70nm.

X-ray microscopy

Microscopy has different x-ray radiation requirements. For enhanced contrast we needed to operate in the water window spectrum (2.4–4nm), where x-ray absorption is dramatically different between water and protein. The x-ray focusing and imaging optics are zone plates (see Figure 7). This diffractive element requires narrow linewidth for tight focusing and sharp imaging. Using Mylar tape in conjunction with nitrogen gas as a high-band-pass filter, we obtained a single narrow band x-ray at 3.37nm with a bandwidth of $\lambda/\Delta\sim 600$.

One percent conversion efficiency (CE) of narrow linewidth was obtained from 532- to 3.37nm x-rays, and even higher CE can be obtained at higher laser pulse energy. Scientists at WonKwang University in Korea have demonstrated x-ray microscopy using our laser.4 They were able to obtain images down to 45nm resolution (see Figure 8).

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References


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