Low-speckle holographic beam shaping of high-coherence EUV sources

Christopher N. Anderson, Ryan H. Miyakawa, and Patrick P. Naulleau

Center for X-ray Optics, Lawrence Berkeley National Laboratory
1 Cyclotron Road, Berkeley, CA 94720, USA

ABSTRACT

This paper describes a method to arbitrarily shape and homogenize high-coherence extreme ultraviolet sources using time-varying holographic optical elements and a scanning subsystem to mitigate speckle. In systems with integration times longer than 100 ms, a speckle contrast below 1% can be achieved.

Keywords: Coherence, Uniformity, Homogenize, Hologram, HOE, Illumination, Lithography, EUV, Speckle

1. INTRODUCTION

It is often desirable to control illumination shape, uniformity, and spatial coherence in imaging systems. Holographic optical elements (HOEs) provide a means to do this by enabling custom far-field patterns to be generated from a coherent source. Controlling the amplitude and phase with a HOE is ideal, however many implementations substitute phase-only or amplitude-only devices because they are easier to fabricate; the tradeoff is that the far-field contains speckle. In applications where the far-field intensity from the HOE is directly viewed (for example, if it illuminates the object in an imaging system, or is the output of a holographic projector), the speckle artifact is a problem because it maps 1:1 to the object of interest. This paper describes a method to shape and homogenize high-coherence extreme ultraviolet (EUV) sources using time-varying phase-only HOEs and a scanning subsystem to mitigate speckle.

2. CALCULATION OF COMPUTER-GENERATED HOES

When calculating the modulating function for a phase-only HOE intended to produce a specific diffraction pattern, two parameters are known:

1. The magnitude of the Fourier transform of the modulating function (the desired diffraction pattern)
2. The amplitude of the modulating function (unity because it is a phase-only device)

Several different algorithms can be used to determine the phase of an object from the amplitude of its Fourier transform.^{1,2} For this application, the error-reduction method is used:

1. Generate the desired magnitude diffraction pattern, $D'(f_x, f_y)$.
2. Add random phase to $D'(f_x, f_y)$, generating $D(f_x, f_y)$ (this seeds a unique speckle pattern)
3. Inverse Fourier transform $D(f_x, f_y)$ obtaining a guess at the modulating signal, $d(x, y)$.
4. Enforce constraints on $d(x, y)$ (force the amplitude to unity).
5. Fourier transform $d(x, y)$ to generate the resulting diffraction pattern, $D(f_x, f_y)$.
6. Enforce constraints on $D(f_x, f_y)$ (set its amplitude to $D'(f_x, f_y)$)
7. Repeat steps 3 through 6 until the magnitude of the result of step 6 matches the desired magnitude diffraction pattern.

This process generates a 2D quasi-continuous phase function $\Phi(x, y)$ whose diffraction pattern closely matches the desired diffraction pattern.

For further information contact cnanderson@lbl.gov

3. FABRICATION OF EUV HOES

Directly encoding $\Phi(x, y)$ as a continuous relief pattern is the most desirable fabrication solution. When this is not practical, the continuous phase can be approximated by discretized (multi-level) versions of $\Phi(x, y)$, with the two-level (binary) case being the easiest to fabricate. When a binary representation is used, a complex conjugate of the desired diffraction pattern shows up in the far-field because the binary operation makes $\Phi(x, y)$ and $\Phi^*(x, y)$ indistinguishable. Also, if the step is not exactly π , a zero-order component will be present. Since the zero-order component is often orders of magnitude smaller in area than the desired diffraction pattern, its intensity can be dominant even for relatively small fabrication errors.

If $\Phi(x, y)$ is encoded onto a spatial carrier before the binary operation, the zero-order component can be separated and the complex conjugate (within a single order) can be mitigated. Using this technique, the phase of the HOE becomes:

$$h(x, y) = \pi/2(1 + \text{sgn}[\sin(2\pi f_c + \Phi(x, y))]) \quad (1)$$

The addition of the carrier causes an angular separation between the zero-order component and the desired diffraction pattern, enabling them to be separated. An EUV phase-only HOE employing a binary relief structure has been previously demonstrated by Naulleau et. al.;³ all HOEs described in this manuscript will be assumed to be fabricated using the approach described by Naulleau et. al.

4. SPECKLE AVERAGING AND A SOLUTION FOR EUV APPLICATIONS

The solution for the amplitude/phase of an amplitude-only/phase-only hologram is not unique; there are an infinite number of solutions, each with a unique speckle pattern. Computationally, these can be accessed by seeding the desired diffraction pattern with a different random phase each time $\Phi(x, y)$ is computed. If speckle is undesirable, it can be reduced by averaging N unique holograms throughout the duration of image capture. In this fashion, speckle contrast can be reduced from unity to $1/\sqrt{N}$.

In visible light applications, HOEs are generally made with liquid crystal displays (LCDs) that support refresh rates up to 60 Hz. MEMS-based devices using arrays of piston mirrors promise orders-of-magnitude higher speed than LCDs,⁴ but megapixel, high-density formats are still not commercially available. For EUV applications, the only way to average multiple unique holograms is to actually fabricate different holograms and mechanically translate them through the illuminating beam during the exposure.

One straightforward approach is to pattern N unique holograms side-by-side into an annulus on a balanced wheel and spin the wheel with a motor (see Figure 1a). For an application requiring $< 1\%$ speckle contrast, $N = 10,000$ unique holograms would need to be averaged. With a 2-mm x 2-mm beam,⁵ the wheel would be 20 meters in circumference (2-mm x 10,000) and would have to spin at a frequency of $1/t$ where t is the exposure time. The markedly large size of the hologram wheel makes this solution impractical; however a smaller wheel with $N = 100$, for example, is reasonable. If a $N = 100$ wheel is used, the remaining 10% speckle contrast ($1/\sqrt{100}$) must be mitigated some other way.

5. SCANNING THE FAR-FIELD GENERATED BY THE HOE

The correlation length (L_c) of a signal is defined as the distance it needs to be translated (in space or time) to decorrelate it from the unshifted signal. For our application, translating the speckle pattern by at least L_c is effectively like having a new speckle pattern to add to the counting statistics. For example, if a 100% contrast speckle pattern is translated horizontally a distance of $10L_c$ at a constant velocity, the integrated intensity will have a speckle contrast of $1/\sqrt{10}$. Likewise, translate it by $100L_c$ and the speckle contrast will drop to $1/\sqrt{100}$. Because the translation is one-dimensional in these examples, the residual speckle contrast will have preferential structure (streaks) in the translation direction. Nonetheless, scanning the far-field generated by the HOE is an effective way to add additional speckle averaging.

For the scanning/speckle averaging process to be effective, L_c needs to be small enough relative to the structure in the far-field that the convolution operation brought about by scanning does not cause significant

Figure 1. (a) Spinning hologram wheel concept; (b) Scanning subsystem concept.

blurring of the desired long-range illumination pattern. Speckle is the result of spatially filtering white noise with the limiting aperture of the optical system (in this case the hologram itself). Its correlation length, therefore, is identical to the Rayleigh resolution limit: λ/NA where NA is the numerical aperture set by the size of the hologram and the distance between it and the observation plane. For an somewhat realistic NA of .001 (2-mm hologram, 1 meters away), a kernel diameter of $100L_c$ would blur the far-field by $100 \cdot 13.5 \text{ nm}/.001 = 1.3 \text{ mm}$.

The coupling of the spinning hologram wheel and the far-field scanners in the proposed system causes a multiplexed sampling effect that is important to understand. The time-evolution of this phenomena is illustrated in Figure 2. Each point on the curve represents the position of the far-field and the hologram that generates it at a single instant in time assuming a circular scan of radius of βL_c and N unique holograms within the spinning hologram wheel (in this diagram, the hologram wheel completes approximately seven revolutions as the scanning system completes one cycle). The plot reveals that each hologram undergoes a sampled convolution with the scanner kernel during the scan. The sampling reaches the nyquist limit when number of samples equals the number number of correlation widths that reside in the circumference of the scan, or $2\pi\beta$. This represents the maximum number of additional speckle patterns that can be added to the counting statistics as a result of the circular scan. In general, the number of correlation length “pixels” that reside within the scan kernel area dictates the maximum number of additional speckle patterns that can be added to the counting statistics by virtue of the scanning process. Consequently, the combined system has a speckle contrast limit of $1/\sqrt{N \cdot N_{scan}}$ where N is the number of holograms on the wheel and N_{scan} is the number of correlation length pixels that reside within the scan kernel.

Accessing all of the “available” samples that reside in the scan kernel requires that the hologram wheel completes N_{scan} revolutions every time the scanner completes one cycle. When this occurs, the scan kernel is nyquist sampled by every hologram on the wheel.

6. DEMONSTRATION

Figure 3 shows a 9-mm x 2-mm, 10% contrast, $L_c = 30 \mu\text{m}$ speckle pattern (a) and the result of convolving it with 1-pixel-wide circles of radii $10L_c$ (b), $50L_c$ (c), and $100L_c$ (d), mimicking the best-case nyquist-sampled scenario. Figure 3 (e) is a detail view of the $100L_c$ scan, showing a RMS speckle contrast of roughly 0.5 % ($1/\sqrt{100 \cdot 2\pi 100}$) and a 5 % intensity variation across the field. If the speckle pattern is designed a-priori to be larger in both dimensions by the diameter of the scan kernel, the field variation effect can be mostly mitigated.

An implementation suitable for the in-development SEMATECH Berkeley 0.5-NA EUV ($\lambda = 13.5 \text{ nm}$) microfield exposure tool (MET) would require far-field dimensions of 12 mm x 2 mm and an individual hologram size of 2 mm x 2mm. With $z = 2 \text{ m}$, this corresponds to an NA of .0005 and $L_c = 13.5 \text{ nm}/.0005 = 27 \mu\text{m}$. With the overfill strategy discussed above, the overfill + scanning has a combined efficiency of roughly 25 %

Figure 2. A representation of the time evolution of the far-field intensity generated by a illuminating rotating hologram wheel and a scanning its output beam. Each point on the curve represents the center position of the far-field and the hologram that generates it at a single instant in time assuming a symmetric scan of radius of βL_c and N unique holograms on the spinning hologram wheel. In this diagram, the hologram wheel completes approximately seven revolutions as the scanning system completes one cycle.

Figure 3. (a) 9 mm x 2 mm, 10% RMS contrast, $L_c = 30 \mu\text{m}$ baseline speckle pattern; (b) with a circular scan of radius of $10L_c$; (c) with a circular scan of radius of $50L_c$; (d) with a circular scan radius of $100L_c$. The red and blue traces are the cross sections in the vertical and horizontal directions, respectively.

(a factor of 0.45 just for the overfill, and another factor of approximately 0.5 from the scanning convolution). This efficiency can be significantly improved if an aspect-ratio-matched scan kernel is used in place of the circle. In addition, the system would need to support exposure times as short as 100 ms. This means the means the $N = 100$, $N_{scan} = 100$ case (1% speckle contrast) would require a 1kHz rotation frequency for the hologram wheel. Figure 4 shows the tradeoff between hologram wheel size and rotation frequency for several exposure time settings below 1 second.

Figure 4. (left) Plot showing the required rotational velocity of the hologram wheel in RPM as the number of holograms within it is varied, for various supported exposure times. This assumes a speckle contrast of 1% in the far-field; (right) Rotational velocity of the hologram wheel in RPM as the wheel diameter is varied, assuming each hologram is 2-mm x 2-mm.

7. A FEW MORE COMMENTS

When the desired far-field intensity is not rotationally symmetric, or whenever a carrier is used, each unique hologram in the annulus must be oriented in the azimuthal direction to preserve far-field orientation as the wheel rotates. Also, spatial carrier phase encoding can enable an additional $\sqrt{2}$ improvement in speckle contrast in inversion-symmetric systems by creating two channels (± 1 orders) that can be independently scanned and averaged in the far-field.

8. WRAP UP

Using previously demonstrated EUV HOEs³ and in-vacuum scanning systems, high-coherence EUV sources can be arbitrarily shaped and homogenized with less than 1% speckle contrast in systems with integration times longer than 100 ms (for example an EUV microscope or EUV lithography tool).

ACKNOWLEDGMENTS

This work was funded in part by SEMATECH and performed at Lawrence Berkeley National Laboratory's Advanced Light Source synchrotron facility which is supported by the DOE, Office of Science, Basic Energy Sciences.

REFERENCES

1. J. Fineup. Reconstruction of an object from the modulus of its fourier transform. *Opt. Lett.*, 3:27–29, 1978.
2. R. Gerchberg and W. Saxon. A practical algorithm for the determination of phase from image and diffraction plane pictures. *Optik (Stuttgart)*, 35:237–246, 1972.
3. P. Naulleau, F. Salmassi, E. Gullikson, and J. A. Liddle. Design and fabrication of a high-efficiency extreme-ultraviolet binary phase-only computer-generated hologram. *Applied Optics*, 46(14):2581–2585, 2007.
4. D. Lopez, V. A. Aksyuk, G. P. Watson, W. M. Mansfield, R. Cirelli, F. Klemens, F. Pardo, E. Ferry, J. Miner, T. W. Sorsch, M. Peabody, J. Bower, M. Peabody, C. S. Pai, and J. Gates. Two-dimensional mems array for maskless lithography and wavefront modulation. *Proc. of SPIE*, 6589(65890S-1):2006.
5. 2-mm x 2-mm is a typical beam size at an experimental endstation at the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California.

This work was supported by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.