How to effectively evaluate a direct laser lithography system

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Measurement uncertainty quantifies performance-related doubt and evaluates the reliability of a direct laser lithography system.

It is common knowledge that obtaining high-quality fabricated products relies on the performance of the instruments used to make them. Accordingly, fully evaluating the reliability of the instruments requires taking into account the ‘measurement uncertainty’ of the results.\(^1\), \(^2\) Measurements convey information about a property of a thing. For example, a measurement might indicate the weight or length of an object. It gives a number to the property of interest. Well-made rulers, clocks, and thermometers might be assumed to be trustworthy and to give the right answers. But for every measurement—even the most careful—there is always a margin of doubt. Quantifying the degree of this uncertainty is key to increasing reliability. The method is complicated by the measuring instrument, the object being measured, operator skill, sampling issues, and the environment, and, as a result, it is not yet widely used in a field as specialized as lithography.

To illustrate the utility of measurement uncertainty, we applied it to a direct laser lithography system (DLLS) that we developed. Its working size is up to 360mm, and its minimum line width is about 0.5\(\mu\)m, enabling it to fabricate various computer-generated holograms (CGHs) from 5 to 360mm in diameter.\(^3\) To assure the performance of the DLLS, we evaluated the moving stages and the writing head module.

For the moving stages, evaluation consisted of the standard uncertainty of a line-positioning error in the radial direction. This error, defined as \(\Delta\), is due mainly to the linearity \((\Delta_1 = p_2 - p_1)\) and the angular motion error \(\Delta_a\) of a linear stage, the run-out error \(\Delta_r\) of a rotary stage, and the centering error \(\Delta_c\) of the DLLS (see Figure 1).

First, we measured \(\Delta_1\) using a commercial heterodyne interferometer on the moving axis of the linear stage. The uncertainty of \(\Delta_1\), defined as \(u_1\), was 4.0nm based on 30 repeated measurements. The second error, due to angular motion of the linear stage coupled with a distance factor (the distance from the connecting part of the writing head and the moving stage to the focal point), is directly measured by an autocollimator and a commercial coordinate-measuring instrument (see Figure 2).

The uncertainty of the angular error \(u_a\) was 8.3nm within a 180mm range. For the run-out error of the rotary stage, we fabricated a 0.8mm circle. We measured the circle with a commercial white-light scanning interferometer (see Figure 3). Using an edge-detection algorithm\(^4\) and a circle-fitting method, we estimated \(\Delta_r\). The uncertainty \(u_r\) of \(\Delta_r\) was 2.5nm at 600rpm. To

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estimate $\Delta_c$ (another dominant factor), we fabricated a spiral pattern on a substrate and extracted $\Delta_c$ using a line-fitting algorithm. In our case, $\Delta_c$ and its uncertainty, $u_c$, were 12 and 6.0nm, respectively. A combined $u_\Delta$, which is the square root of the sum of each uncertainty squared, was 11.3nm. We obtained different uncertainties from 30 repeated measurements for better estimation.

The overall (so-called expanded) uncertainty, stated at level of confidence of 95%, can be determined using a coverage factor, $k$. Multiplying the combined standard uncertainty $u_\Delta$ by the coverage factor gives the expanded uncertainty, defined as $U = ku_\Delta$. The coverage factor used in this case was $k = 2$. The expanded uncertainty $U$ was 22.6nm. The calculated wavefront error due to $U$ was about 5.19nm for a typical case of CGH. We measured the wavefront error in a 98mm-diameter CGH using a commercial Fizeau interferometer. The result was 0.0063$\lambda$ ($\lambda = 632.8$nm) in rms value (see Figure 4).

Finally, we estimated the focusing error of the writing head module. The calculated depth of focus with respect to the writing beam of 488nm and the numerical aperture of 0.9 was 301.2nm. The autofocus controller showed a 280nm focusing error. This result is sufficient to satisfy the tolerance specification. Ultimately, we successfully fabricated a 300mm-diameter CGH using the results reported here.

In summary, a measurement result can be only complete if it is accompanied by a statement of the uncertainty of the process. Consequently, applying measurement reliability to the DLLS enabled us to objectively estimate uncertainties for the first time. As a next step, we plan to comprehensively evaluate the DLLS, including the uncertainty of the stability of the light source.

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