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UCRL-CONF-229266

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March 21, 2007

7th EUSPEN International Conference
Bremen, Germany
May 20, 2007 through May 24, 2007

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Imprinting Continuously Varying Topographical Structure onto Large-Aperture Optical Surfaces using Magnetorheological Finishing

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Abstract

Over the past four years we have advanced Magnetorheological Finishing (MRF) techniques and tools to imprint complex continuously varying topographical structures onto large-aperture (430 × 430 mm) optical surfaces. These optics, known as continuous phase plates (CPPs), are important for high-power laser applications requiring precise manipulation and control of beam-shape, energy distribution, and wavefront profile. MRF's unique deterministic-sub-aperture polishing characteristics make it possible to imprint complex topographical information onto optical surfaces at spatial scale-lengths approaching 1 mm and surface peak-to-valleys as high as 22 μm. During this discussion, we will present the evolution of the MRF imprinting technology and the MRF tools designed to manufacture large-aperture 430 × 430 mm CPPs. Our results will show how the MRF removal function impacts and limits imprint fidelity and what must be done to arrive at a high-quality surface. We also present several examples of this imprinting technology for fabrication of phase correction plates and CPPs for use in high-power laser applications.

1 Primary function of CPPs

CPPs are newly developed large-aperture ultra-precision diffractive optics used in high-power kilojoule- and megajoule-class laser systems to adjust and fine-tune a laser beam to a prescribed size and shape while maintaining the coherent properties of the laser light. CPPs fall into the category of diffractive optics with which we take advantage of the apparent bending of light waves in response to small topographical changes on an optical surface. These optics are made by imprinting a prescribed continuously varying phase profile onto an optical surface using MRF, as shown in Figure 1. These topographical changes are computer generated to achieve the required energy contours. This near-field topography is the key to enabling detailed control of the laser beam characteristics at the focal plane at high power. It can be designed to convert a square or circular laser beam footprint to an elliptical or circular spot of prescribed lateral dimensions. Other spot shapes, such as triangles, squares and closed polygons, are also possible. This continuously varying surface topography perturbs the incoming laser beam wavefront before, or after, passing through the final focusing element to yield a beam footprint at the focal plane with the desired characteristics.

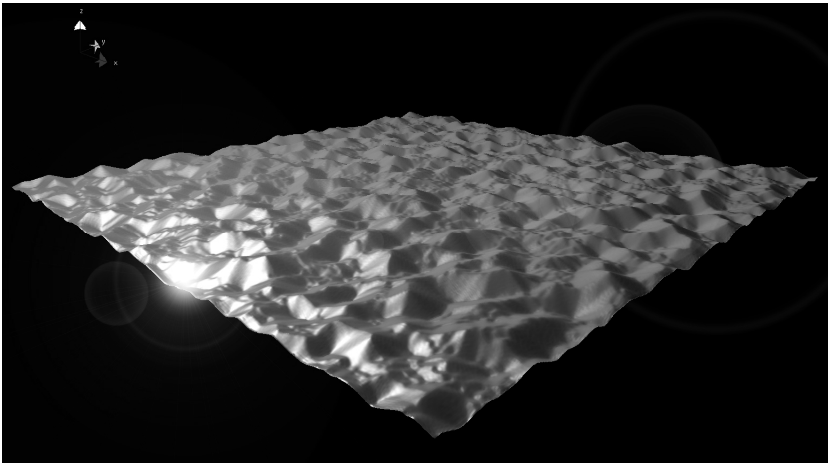

Figure 1: Continuously varying topographical CPP pattern with an 8.6 μm P-V imprinted onto a 430- × 430- × 10-mm fused silica substrate using MRF.

2 MRF Imprinting

MRF offers a direct approach for imprinting smooth topographical features onto optics without the use of lithographic masks or master plates. It is an advanced optical finishing process combining interferometry, precision equipment, and computer control. It utilizes a sub-aperture polishing tool, or removal function, generated by the interaction of a magnetic field and an iron-based MR fluid containing microscopic abrasive particles such as ceria or nano-diamonds. MRF is a deterministic polishing technique because the polishing tool effectively doesn't change. Because the removal function is interferometrically characterized and highly stable, the system can efficiently deliver high precision parts. Other advantages are that the polishing tool is easily adjusted, and conforms perfectly to the optical surface, enabling topographical polishing.

MRF's deterministic polishing capability, wide array of available removal functions, and close interplay with interferometry enable imprinting of diffractive phase structure that varies continuously across the whole beam aperture with no sharp discontinuities or phase anomalies. Material removal rates ranging between 0.025 - 1 mm^3 per minute can produce an imprinted optic in 50-75 hours. The technology is capable of, and routinely produces, highly precise topographical profiles with errors of about 30 nm rms over the optic aperture that yields highly efficiency plates (> 99 percent) whose characteristics are precisely defined. Optical surface finish is also maintained at better than 4.0 Angstroms rms roughness.

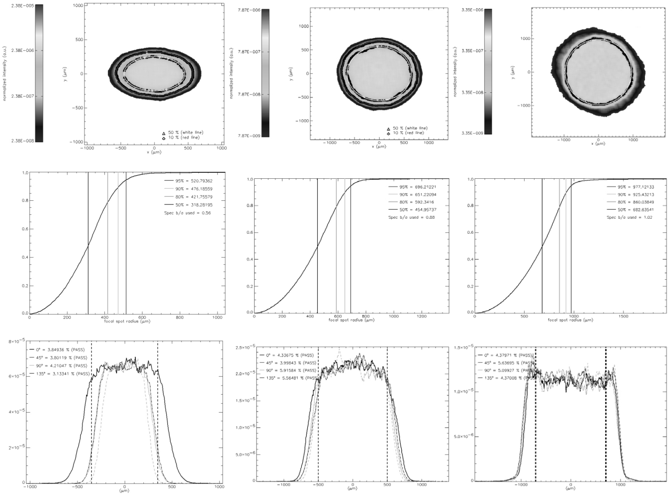

Figure 2: Examples of large-aperture CPPs manufactured and tested at LLNL. Left: 50-degree outer cone implosion CPP, eccentricity of 0.56. Center: 23-degree inner cone implosion CPP, eccentricity of 0.88. Right: 2-mm far-field spot illuminator CPP, eccentricity of 1.00.

Figure 2 and Table 1 show the far-field characteristics for three different CPP types that have been designed and tested at LLNL. Twelve unique CPP designs have been manufactured and tested to date.

Table 1: Examples of CPP performance parameters versus specification for large aperture CPPs manufactured using MRF

	Specification	Measured	Pass/Fail
50-degree outer cone implosion CPP			
80% Encircled Energy Radius (µm)	421.0 ± 15.0	421.8	PASS
90% Encircled Energy Radius (µm)	472.0 ± 15.0	476.2	PASS
95% Encircled Energy Radius (µm)	515.0 ± 15.0	520.8	PASS
Individual Lineout RMS Deviation (%)	5.0	4.2	PASS
2D RMS Deviation over Central Area (%)	5.0	4.5	PASS
50% Eccentricity (a = 451.2, b = 252.4)	0.56 ± 0.1	0.56	PASS
23-degree inner cone implosion CPP			
80% Encircled Energy Radius (µm)	594.0 ± 15.0	592.3	PASS
90% Encircled Energy Radius (µm)	652.0 ± 15.0	651.2	PASS
95% Encircled Energy Radius (µm)	696.0 ± 15.0	696.2	PASS
Individual Lineout RMS Deviation (%)	7.0	5.9	PASS
2D RMS Deviation over Central Area (%)	5.0	4.7	PASS
50% Eccentricity (a = 451.2, b = 252.4)	0.88 ± 0.1	0.88	PASS
2-mm far-field spot illuminator CPP			
80% Encircled Energy Radius (µm)	860.0 ± 15.0	860.0	PASS
90% Encircled Energy Radius (µm)	923.0 ± 15.0	925.4	PASS
95% Encircled Energy Radius (µm)	976.0 ± 15.0	977.1	PASS
Individual Lineout RMS Deviation (%)	6.5	5.6	PASS
2D RMS Deviation over Central Area (%)	6.5	5.7	PASS
50% Eccentricity (a = 451.2, b = 252.4)	1.02 ± 0.1	1.02	PASS

Work performed under the auspices of the US Department of Energy by UC, Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.