

Manufacturing Large Spherical and Cylindrical Laser Focusing Gratings by Scanning Beam Interference Lithography

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Abstract: Volume production of large gratings with excellent efficiency and wavefront performance is well established, making them a simple, low-cost alternative to large lenses, in addition to offering advantages only obtainable by freeform and diffractive optics.

1. Introduction

The performance of many laser-based optical systems is improved by increasing beam size, often to enable higher intensity. Applications in materials processing range from cutting to annealing, while those in scientific research span laser fusion to particle acceleration. However, costs associated with large-format optical components such as lenses and mirrors as beam size increases can quickly become prohibitive due to fabrication challenges primarily in material production, polishing, and metrology. This paper considers an alternative approach to traditional optical components for large-format optical systems that has received relatively little attention to date: the use of diffraction gratings for basic beam management functions. As a simple example, by varying the period and orientation of grating fringes across its aperture, a grating can perform point-to-point imaging just like a lens (Fig. 1).

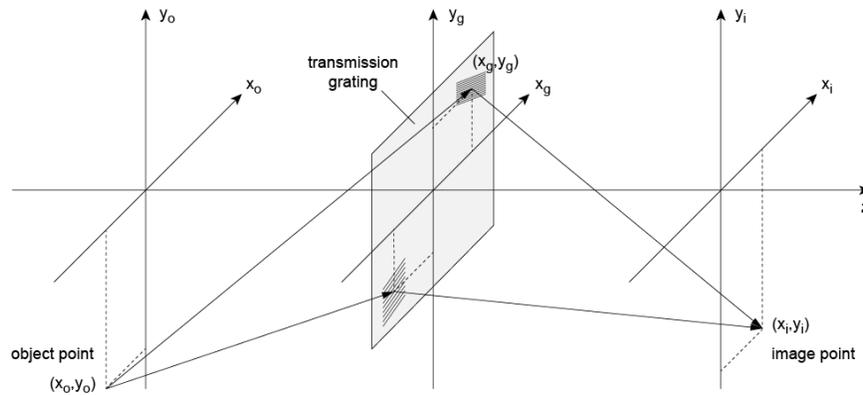


Figure 1. A grating with variable fringe period and orientation performs diffraction-limited point-to-point imaging.

Extremely high-performance, meter-class diffraction grating manufacturing is now well established [1]. This technology was driven by ultra-high-intensity, chirped-pulse-amplification laser systems [2]. The gratings are made on optical flats, for which the manufacturing processes are also well developed. Very high diffraction efficiency (> 95%) of collimated beams and excellent wavefront error ($< \lambda/4$ peak-to-valley) are routinely achieved with gratings up to 1 meter in size. What is often not appreciated is that only grating fringe patterning challenges prevent similarly performing gratings from generating nonplanar wavefronts, for cylindrical and spherical focusing to aberration correction. Below we describe how Scanning Beam Interference Lithography (SBIL) [3] allows highly flexible fringe patterning, unlocking myriad possibilities for gratings in managing large beams and offering the potential for simpler, more cost-effective large-format optical systems.

Gratings do have limitations, such as spectral bandwidth. Because angle and wavelength are intimately coupled, complex wavefront manipulation via gratings requires relatively narrowband beams. Polarization must also be considered, though some designs can be made quite polarization independent, and many laser systems are polarized. Despite these restrictions, advantages of gratings often surpass any disadvantages. In addition to the potential for a simpler and lower-cost solution, gratings also offer the ability to generate freeform wavefronts for additional cost and weight reduction through elimination of components. Because these complex wavefronts are produced with a fully deterministic method, use of large-optics metrology for in-process feedback is not as critical, further reducing production costs. And finally, with gratings it is possible to incorporate additional functionality useful for laser systems within a single compact component, such as beam homogenization for speckle reduction.

2. SBIL enables nonplanar wavefront diffraction

A helpful way to think about the relationship between grating diffraction and wavefront is to recognize that light which diffracts off of equivalent points on neighboring grating fringes has an optical path difference of m

wavelengths, where m is the diffraction order. For plane waves this interpretation leads to the well-known grating equation, $\sin\theta_m = \sin\theta - m\lambda/\Lambda$, where θ is the angle of incidence, θ_m is the angle at which the m^{th} order is diffracted, λ is the wavelength of light, and Λ is the grating period. It also simply demonstrates how grating fringe position can be programmed to achieve an arbitrary diffracted wavefront.

Actually manufacturing a grating with a complex grating fringe program is not so straightforward. Prior to coherent lasers and sensitive photoresist processes, gratings were generally patterned by mechanical ruling engines, which write individual lines sequentially. Sophisticated, stable, DMI-based engines could pattern very large and even complex grating profiles flexibly. However, the process is slow and subject to mechanical imperfections associated with wear and environmental variations over the long write times. Hence only “masters” can be written this way, so production gratings are “replicas” which exhibit further imperfections resulting from the replication process. Holographic gratings written by two-beam interference introduced a cost-effective path to more rapidly produce high-quality gratings free from ruling-engine and replication errors. However, this approach restricts the flexibility with which gratings of arbitrary periods and especially spatially varying periods can be made. Furthermore, it introduces other types of diffracted wavefront errors resulting from writing beam aberrations, and is difficult and expensive to scale to larger sizes.

Scanning Beam Interference Lithography (SBIL) combines the best of both worlds – the patterning flexibility and large-size capability of mechanical ruling engines with the speed and reduction of grating fringe errors afforded by holographic writing [3] (Fig. 2). Besides the excellent patterning performance (period repeatability better than 10 ppb, diffraction efficiency standard deviations < 1% over very large areas, and superb diffracted wavefront error), there is no fundamental limit to the substrate size. And, SBIL is naturally flexible, enabling a simple programmable approach to spatially varying the grating period and orientation during the writing process.

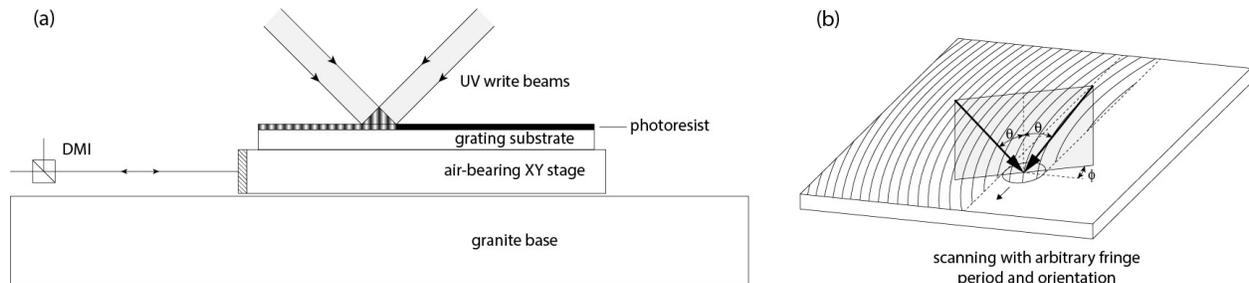


Figure 2. (a) Principle of SBIL; the UV write beam intensity is stationary, while the interference fringe pattern is precisely locked to the substrate movement via a 2-axis displacement measuring interferometer (DMI) and air-bearing stage system. (b) By varying the write beam intersection angle θ and orientation ϕ while maintaining fringe locking, it is possible to write arbitrary fringe patterns over very large substrate areas.

3. Examples

One example of a grating with a programmable fringe pattern that generates a beneficial laser beam wavefront is shown in Fig. 3. Here a collimated 1064 nm laser beam is incident at 30° on a 200 mm \times 200 mm grating. The grating is programmed to diffract the light uniformly onto an 800 mm long line focus 500 mm below the center of the grating in a focal plane 1 m behind the grating (Fig 3(d)). Figs. 3(a) and (b) show the required local period and orientation over the grating area, while (c) plots a grating vector with magnitude equal to the local grating frequency (inverse of period) and direction perpendicular to the grating fringes. Such a grating is useful for high-intensity laser line generation for materials processing in place of large-format cylindrical lenses, which are difficult and expensive to manufacture.

As a second example, large transmission gratings were found to be the most optimal solution for steering and focusing the ultra-high-intensity 1053 (1 ω) and 351 nm (3 ω) beams at the end of the Laser Megajoule (LMJ) system at the Commissariat à l’Energie Atomique (CEA) in France [4] (Fig. 4(a)). CEA designers found that combinations of plane and parabolic focusing mirrors led to cumbersome solutions, and also suffered from laser-induced damage threshold (LIDT) limitations, especially at 351 nm. They explored refractive designs using aspheric prismatic lenses to focus the UV light, but couldn’t arrive at sufficiently simple solutions capable of handling wavelength separation and other constraints. When completed, the LMJ system is expected to comprise a total of 176 beams, each 400 mm \times 400 mm square with a 1 ω steering and 3 ω steering and focusing grating at the end. These gratings are now in full-scale volume production, with many dozens successfully manufactured to date.

The 8 meter focal length 3 ω gratings produce a diffraction-limited spot in the vacuum target chamber with a diameter of about 10 μm . The example shown is a 470 mm \times 420 mm fused silica transmission grating designed for 25° angle of incidence and diffraction at 351 nm. Focusing is achieved by a fringe frequency that varies between 2230 and 2380 lines/mm, and fringe orientation that varies by about 3° . The diffracted wavefront error is comparable to typical reflected wavefront error resulting from substrate surface flatness alone (Fig. 4(b)).

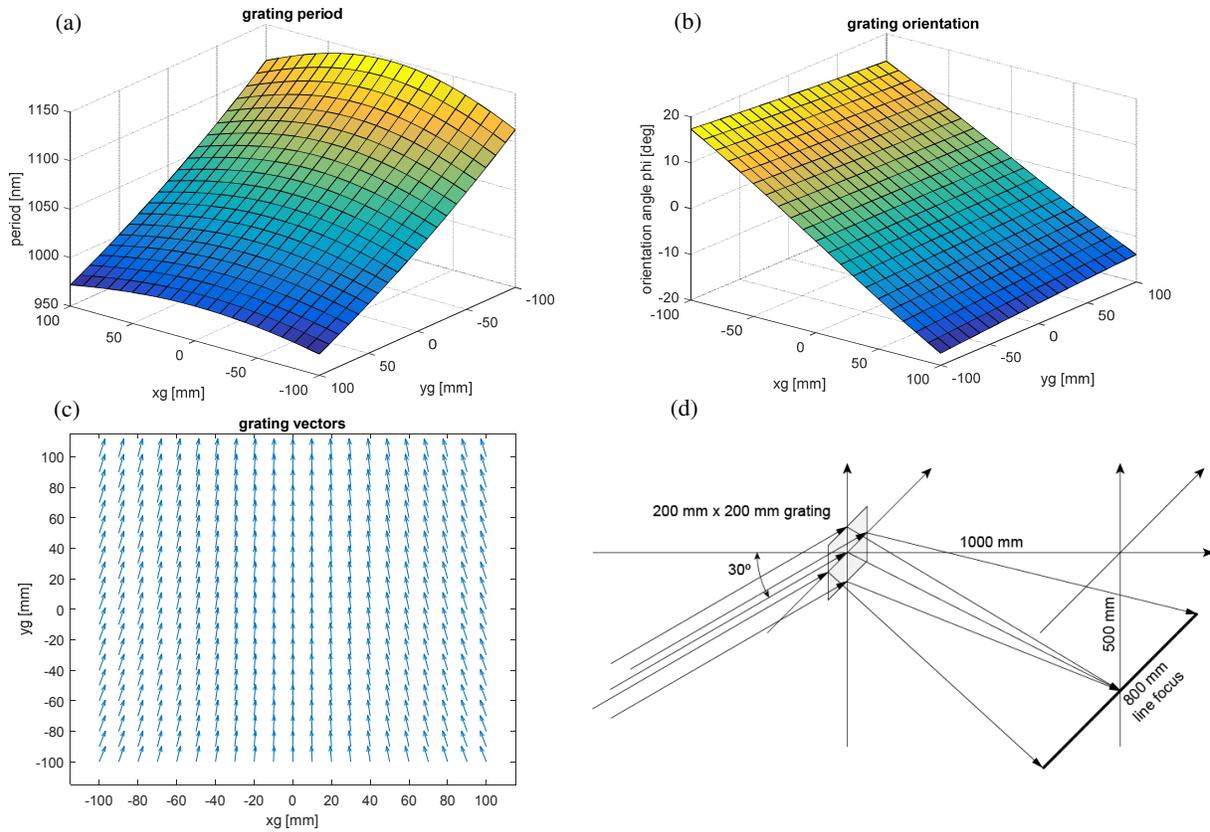


Figure 3. Theoretical period and orientation on 200 mm \times 200 mm grating to create an 800 mm line focus from a collimated 1064 nm laser beam. (a) and (b) show the period and orientation angle ϕ (refer to Fig. 2.); (c) shows a map of the grating frequency and orientation vector; (d) geometry.

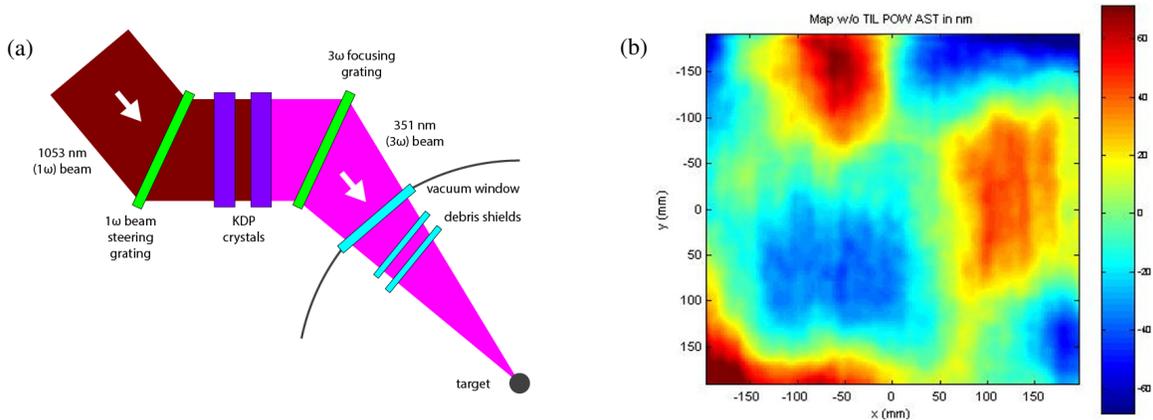


Figure 4. (a) Beam steering and focusing gratings in CEA's LMJ laser system. (b) Diffracted wavefront error measured after focus by an Imagine Optic HASO Shack-Hartmann wavefront sensor: 140 nm peak-to-valley and 27.6 nm RMS (tilt, power, astigmatism removed). At 351 nm and 25° angle of incidence and diffraction, this grating has average diffraction efficiency of 93.1% (includes second surface reflection loss).

4. Conclusions and references

Due to their flexibility and potential for simplification and cost reduction, diffraction gratings should be considered for spherical and cylindrical focusing as well as freeform wavefront management in large optical systems.

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