Efficient generation of large diffraction gratings with a grating interferometer

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The advantages of a grating interferometer for the generation of large diffraction gratings are demonstrated. In a one- and a two-stage process, high-quality gratings of 120 and 200 mm, respectively, were made with optics no larger than 50 mm together with an argon-ion laser with no line narrowing or beam stabilization and a rotating diffuser for improved beam uniformity. © 2001 Optical Society of America

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1. Introduction

There is a growing demand for large efficient high-quality diffraction gratings, principally arising from the increasing development and use of chirped-pulse-amplification laser systems. The current high cost of gratings for these systems is a significant factor and is a consequence of the current manufacturing technique Figure 1 shows the principle of the holographic technique for recording large high-groove-density gratings. Well-collimated beams are required for generating aberration-free gratings, and this implies the need for expensive high-quality optics whose size is greater than that of the grating being recorded. Further, the coherence must be high, demanding the use of a single axial TEM_{00} mode of the recording beam and restricting the usable power from the laser source. The combination of low power and large area together with the need for high coherence leads to long exposure times and a critical requirement on the mechanical stability of the system. This limits the grating size that can be realized.

Relaxation of these requirements would lead to the more-widespread availability of lower-cost large gratings and would make it feasible for individual groups to make gratings for their own applications. Such a relaxation was demonstrated with an elegant scheme proposed by Hershey and Leith[1] that offered a number of advantages over existing techniques. We report results from a recent program[2] that included an investigation of the advantages of this scheme for the fabrication of large gratings.

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2. Hershey and Leith Grating Interferometer

Figure 2 shows the interferometer in its simplest form. It comprises a grating G1 with groove density n lines/mm and two gratings G2 with groove density $2n$ lines/mm. The two first orders diffracted from G1 are incident on G2A and G2B, and the -1 and the $+1$ orders of G2A and G2B, respectively, interfere to record a grating G3 with groove density $2n$ lines/mm. This grating interferometer has the remarkable property that, if the groove densities are as specified and if the geometry is exactly as shown, a stable high-contrast straight fringe pattern will be formed, even if the incident beam has neither spectral nor spatial coherence. This property is demonstrated and the mathematical proof given in Ref. 1.

In principle this implies that an incoherent white-light source could be used. Unfortunately the use of such low coherence would be experimentally difficult, because it would place too tight a requirement on the exact geometry and groove densities. However, these tolerances are greatly relaxed for a laser source, even one with a broad bandwidth, multimode beam, and low directional stability, and thus would enable the laser to be chosen for maximum power (to give minimum exposure time) and reliability. For example, the full bandwidth of a single line from an argon-ion laser makes an ideal source without the need for internal etalons and directional control devices and allows large tolerances to be placed on the geometry and groove densities in the interferometer.

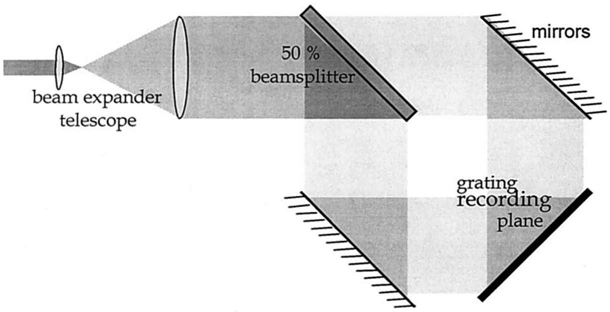

Fig. 1. Typical arrangement for recording gratings.

One aspect of the relaxation of the spatial-coherence requirements is that the interferometer does not require the incident beam to be collimated or aberration free. This is a consequence of the proof given in Ref. 1 but can also be intuitively appreciated as arising from the symmetry of the arrangement that leads to identical aberrations on the two recording beams at G3. These aberrations exactly match on a flat surface at G3 and in consequence cancel to give the same perfectly straight fringe pattern as would be obtained with two aberration-free wave fronts. The use of a diverging beam, for example, enables the generation of a large grating using only small-aperture gratings (G1, G2A, and G2B) and optics. A simple property of the generated G3 grating in this mode of operation[1] is that the number of grooves it contains is equal to the sum of the number of grooves covered by the beams incident on the G2 gratings plus twice the number of grooves covered by the beam incident on the G1 grating. For example, if the three interferometer gratings are equal in diameter, the generated grating G3 can have a diameter three times as large, and with, say, 5-cm gratings it is possible to produce a 15-cm grating directly.

The low requirement on coherence enables a beam homogenizer to be used to generate recording beams with a smooth and flat intensity distribution, and this leads to the recording of efficient high-quality gratings. In simplest form a rotating diffuser before G1 will eliminate effects from beam and grating defects. The requirement for a low-coherence source also implies that only the geometry of the interferometer needs to have high stability. The tolerances on the pointing and profile stability of the laser, and on the

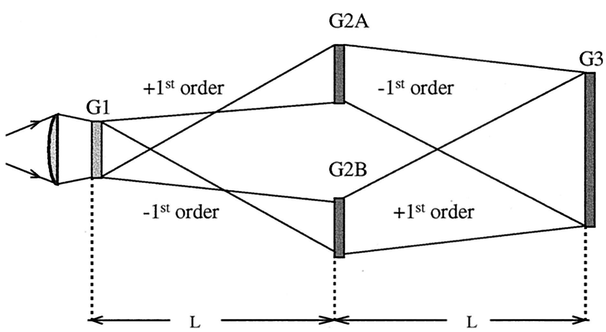

Fig. 2. Hershey and Leith grating interferometer.

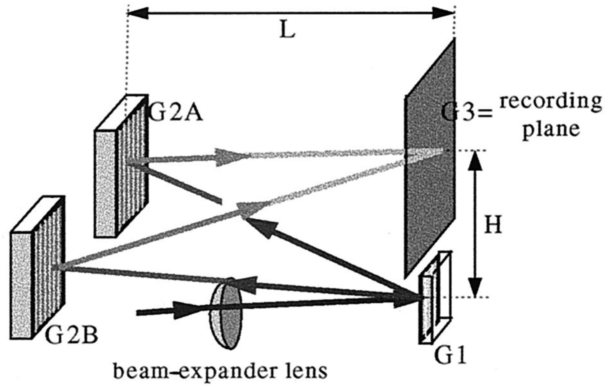

Fig. 3. Grating interferometer using reflection gratings.

mechanical stability and optical quality of relay optics, are large.

One further relaxation of optical tolerances arises from the symmetry of the interferometer, which leads to a cancelation not only of aberrations originating from grating G1 but also of any matching aberrations on G2A and G2B.

We have discussed the principal features of the grating interferometer that allow the recording of a grating up to three times larger than the optics used. The process can be taken a stage further to generate even larger gratings with the same system. To do this, two identical gratings are made in the interferometer, each with a diameter three times larger than that of gratings G1 and G2. These gratings are substituted into the interferometer to replace the original G2 gratings, and the beam-expansion optics are changed to ensure that the beams now fill these new G2 gratings while maintaining the same beam size at G1. The resulting second-generation G3 grating will then be 2.33 times the diameter of the new G2 gratings or 7 times the diameter of the original gratings. In principle this process can be repeated as many times as desired, and each time there will be a magnification of at least 2. An additional benefit of the successive use of the interferometer to generate ever-larger gratings is that it is only in the final stage that tolerances on the geometry need to be met closely. This arises because, if two gratings are recorded consecutively in identical positions at G3 but in the presence of wave-front aberrations, these imperfect gratings can be made identical and consequently contribute identical aberrations to the two arms of the interferometer when used subsequently as G2A and G2B. When these combine to record a new G3, these aberrations cancel.

3. Experiment

A reflection-grating version of the interferometer was used for the tests and is shown schematically in Fig. 3. This includes an out-of-plane angle to ensure a vertical separation of G1 and G3, the recording now being in the same vertical plane as G1. The properties of the interferometer remain unchanged by this modification.

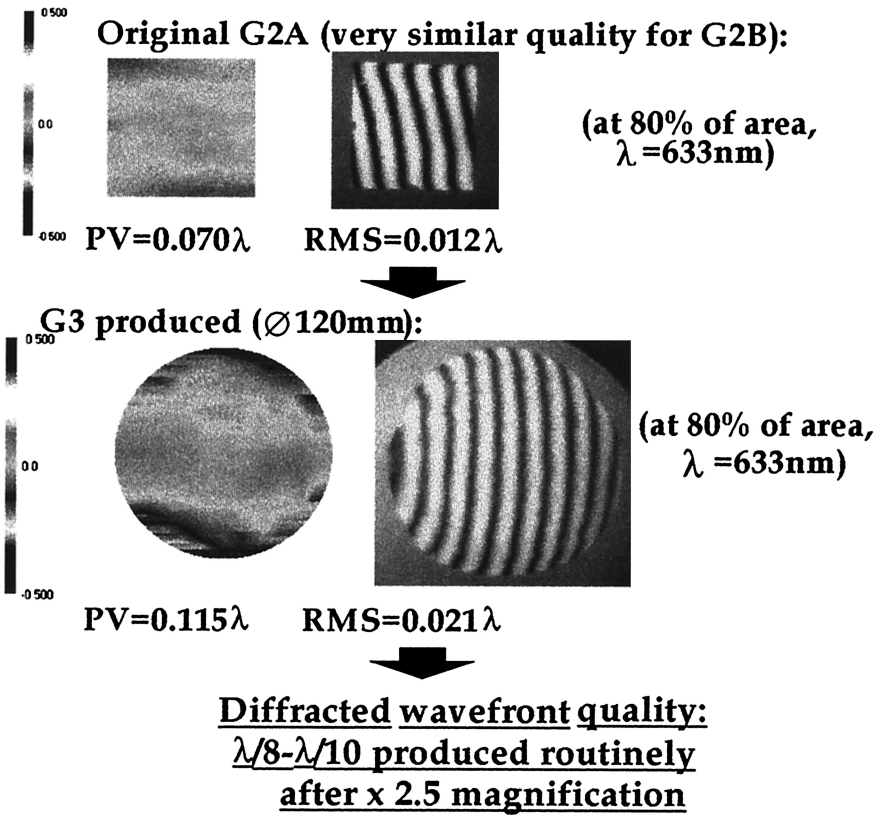

Fig. 4. Diffracted wave-front quality of the small commercial gratings used in the interferometer (top) and a large grating produced by the grating interferometer (bottom).

The parameters chosen for the tests were $L = 1.4$ m; G1 groove density, 600 lines/mm; G2 groove density, 1200 lines/mm. The G1 grating size was 25 mm, and the G2 gratings were 50 mm, indicating a maximum magnification of 2.5 and a maximum available size for G3 of 125 mm. The recordings were made by optical lithography in photoresist with a wavelength of 458 nm from an argon-ion laser. The laser was operated in a multiline non-line-narrowed mode giving its natural coherence length of less than 1 cm and an output power of as much as 1 W at 457 nm in TEM_{00} mode. No special beam stabilization was required. Indeed, the input beam to the interferometer was scrambled with a rotating diffuser in order to ensure a spatially smooth distribution over the recording plane. The generated grating at G3 was recorded with photoresist spun onto 120-mm blanks. The required exposure of the resist was approximately 250 mJ/cm^2, necessitating exposure times of several minutes for these 120-mm gratings.

A setup procedure was evolved to ensure good quality for the recorded gratings. The principal features of the procedure were the positioning of a high-quality 50-mm 1200 lines/mm analyzer grating in the recording plane and observation of the difference or moiré fringes between the interferometer fringes and the grooves of this grating. Initially the rotating diffuser is removed to improve the fringe visibility when the interferometer is out of alignment. Distorted fringes are generally observed, and the interferometer is then adjusted to give straight fringes. Fine adjustment can then be made with the diffuser in place and set to give maximum diffusion. In this case a misalignment leads to a contrast reduction as well as a distortion of the fringes, and maximizing both the fringe contrast and straightness gives the best overall alignment. This observation technique was also used to investigate the long-term temporal stability of the fringe pattern being recorded. With the interferometer on a single stabilized 6 ft $\times$ 4 ft (1 ft = 30.48 cm) table and the laser and relay optics on a separate table, high fringe stability was observed allowing exposure times of several hours. This would enable the recording of, for example, gratings of dimension greater than 50 cm with a modest 1-W laser, if the interferometer had a transmission of, say, 10% (typical).

Grating diameters of 120 mm were recorded in the grating interferometer and, following development and aluminizing, placed in a test interferometer to measure the wave-front quality of the diffracted first order. A result is shown in Fig. 4 along with the wave-front quality of one of the gratings G2 used to record it. It can be seen that the peak to valley is $\lambda/9$ and the rms error is $\lambda/50$, almost as good as with the smaller original grating. A small residual astigmatic error was observed, but simple aberrations such as this can be corrected by a small adjustment of the interferometer, regardless of the aberration source.

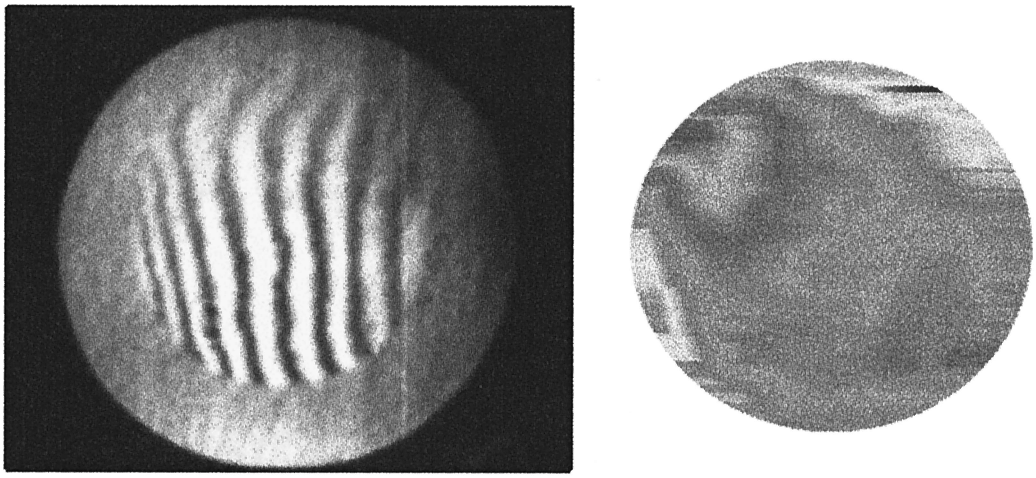

Fig. 5. Diffracted wave-front quality of a second-generation 200-mm grating.

The primary aim of this program was to show the feasibility of generating large aberration-free gratings and required the recording of a fringe pattern with high groove linearity, parallelism, and spacing uniformity. Since high efficiency and uniformity of exposure do not affect these parameters, their optimization was not undertaken, and we note that the optimization of the resist technology for efficiency and uniformity has been well refined by the commercial grating companies. However, simple exposure adjustment together with the use of minimum resist thickness led to efficiencies of 30% in each of the two first orders. This value was close to the theoretical maximum for the groove density and wavelength and demonstrated the excellent fringe stability of the interferometer.

A two-stage recording to generate a yet larger grating was also tested. Two identical 120-mm gratings were recorded as above and inserted into the interferometer in place of the original 50-mm G2 gratings. With appropriate adjustments including an increase in the out-of-plane angle in the interferometer a grating was recorded on a 200-mm blank. The geometry of this second stage would have allowed for the recording of a grating of size up to 265 mm if a suitable blank had been available. The wave-front quality of the first order from this second generation grating is shown in Fig. 5. This gave a peak-to-valley error of $\lambda/3$ and an rms error of $\lambda/12$. The residual error is largely correctable by improved alignment of the interferometer. The use of a 120-mm grating, recorded in the first stage and used as a larger analyzer grating in the second stage, should help to improve the alignment accuracy of the instrument.

4. Conclusion

A grating interferometer has been demonstrated to enable the generation of large high-quality holographic gratings with small optics, a low-coherence argon-ion laser, and a beam homogenizer. Only the two small gratings (G2) need to be of good optical quality, and the alignment tolerances of the interferometer are straightforward to achieve. Successive use of the interferometer allows for the manufacture of gratings with ever-increasing size.

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