Concave holographic grating: optimization of the diffraction efficiency

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The experimental comparison between two concave holographic gratings with identical recording geometries and different exposure conditions demonstrates some possibilities for the optimization of the integral diffraction efficiency.

1. Introduction

In a previous paper we examined local and integral efficiencies of a concave holographic diffraction grating at different wavelengths.[1] This flat-field quasi-sinusoidal grating (called hereafter the initial grating) is designed for a color-measuring spectrograph in the range $\lambda = 380$–780 nm; it has a 92-mm active area diameter, a 100-mm blank diameter, a 211-mm radius of curvature, a period $d = 1.26135$ μm, and is coated with aluminum.

The radial groove depth distribution over the meridional grating diameter is found to have approximately a Gaussian form, which is shown in Fig. 1 with a dashed curve. Modulation (the ratio of groove depth to period h/d) ranges from a central maximum of 15.9% (intermediate) to 4.2% near the edges (very low), a ratio of almost 4:1. On the other hand, in the spectral region mentioned, λ/d varies from 0.30 to 0.62, i.e., definitely outside the scalar domain. Therefore we can expect anomalies and different behavior for the TE and TM polarizations. The combination of these two factors explains the three types of measured local efficiency maps: (i) without anomalies, e.g., at $\lambda = 600$ nm, (ii) with anomalies in TE and TM polarizations simultaneously, e.g., at $\lambda = 441.6$ nm, and (iii) with anomaly only in TM polarization, e.g., at $\lambda = 676.4$ nm (see Fig. 4 in Ref. 1).

The total diffraction efficiency for Gaussian illumination was calculated by summing all the local efficiency values multiplied by weighting coefficients expressing the relative local intensity of the incident beam. It was shown in this way that the integral efficiency is optimized when the illuminating beam $1/e$ diameter Φ_B is 30–40% of the active grating diameter Φ_G (see Fig. 8 in Ref. 1). Use of beams with smaller diameters ($\Phi_B < 30\%\Phi_G$) or with greater diameters ($\Phi_B > 40\%\Phi_G$) is expected to result in a decrease in efficiency.

Finally, another interesting prediction was made in Ref. 1: If the radial groove depth distribution is modified to range from, say, 12% in the center to 6% at the edge (giving a ratio of only 2), one could expect an absolute increase of the integral efficiency in the blue region of 4–6% (assuming that the illuminating beam has a diameter $\Phi_B > 30\%\Phi_G$). In other words, the efficiency of the initial grating could be optimized in such a manner.

The purpose of the present paper is to check experimentally the local and integral efficiency behavior of the optimized grating, which is recorded at the same geometrical conditions as the initial one, but with its groove depth distribution modified as proposed in Ref. 1. Some comments are made on the local efficiency behavior in the design and use of concave holographic gratings.

2. Experiments on the Optimized Grating

A. Groove Depth Distribution

The absolute ± 1-order local diffraction efficiencies were measured for TE and TM polarizations at wavelengths of $\lambda = 441.6$, 632.8, and 676.4 nm. The laser beam was directed at the blank surface in a network of 69 equidistant points, always emerging from the source's operating position as recommended by the manufacturer. Experimental data were compared with theoretical values, which are calculated in the conical diffraction regime as a function of the

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Received 19 June 1991.
0003-6935/92/255317-03$05.00/0.

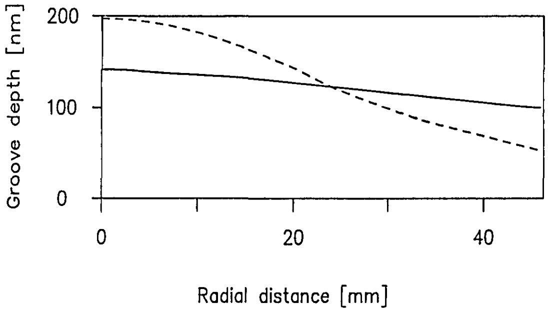

Fig. 1. Radial groove depth distribution $h(r)$ for the initial grating from Ref. 1 (dashed curve) and for the optimized grating (solid curve).

modulation h/d assuming a sinusoidal groove shape. The averaged radial modulation distribution so obtained is given in Fig. 1 in comparison with the initial grating dependence from Ref. 1. It is evident that the new distribution is also nearly Gaussian and is really modified as suggested in Ref. 1. The maximum modulation in the center is 11%, and the minimum modulation at the edge is 8%, which gives a ratio of approximately 1.4:1. This groove depth modification is achieved by an appropriate change in the holographic exposure conditions (e.g., the recording beamwidth).

B. Local Efficiency

The local efficiency as measured in the operating regime, recommended by the manufacturer, is shown in Fig. 2 in the blue (λ = 441.6 nm, He–Cd laser) and in the red (λ = 676.4 nm, Kr^+ laser) regions of the visible spectrum. The figure presents the results for TE and TM polarizations on the meridional grating diameter together with the corresponding data for the initial grating. One can notice that the optimized grating efficiency at 441.6 nm is much more uniformly distributed over the diffractive area for the optimized grating than for the initial grating. The local central minimum in the TM polarization at 676.4 nm is also significantly shallower.

The local anomalies can be visualized when the grating is illuminated by one strong diverging beam covering its surface entirely. Registering the diffracted first-order beam cross section on a photoplate, which is moved successfully away from the grating in the focal region in steps of 0.5 mm, one obtains the picture shown in Fig. 3. The minimum-width spot represents the meridional focal image of the point source. The larger elliptical spots are defocused images of the same source but in the vicinity of the meridional focus. The photograph illustrates the situation at 676.4 nm, which is interesting with its different polarization behavior. The deep TM anomaly appears as a black horizontal line, but only out of focus. In the focus one detects an averaged integral diffraction efficiency value.

C. Integral Efficiency

In order to follow the connection between the local and integral efficiency properties we measured the total efficiency illuminating the grating by a set of micro objectives with magnifications of 0× (laser beam without objective), 3.7×, 8×, 12.5×, 25×, 50×, and 100×. The $1/e$ diameter of the beam when it reaches the grating surface, i.e., at a distance of 231 mm from the source, depends not only on the magnification but also on the wavelength, as is shown in Table 1. The measured total efficiency values are plotted in Fig. 4 as functions of the relative beam diameter Φ_B/Φ_G. These dependences are in good accordance with the numerical simulations from Ref. 1.

In cases without anomaly (e.g., TE at 676.4 nm) the efficiency decreases smoothly and monotonically from the maximum local value in the center to a moderate integral value when the diverging beam tends to cover the whole grating, the less effective marginal region included. In cases with anomaly (e.g., TM at 676.4 nm; TE and TM at 441.6 nm; unpolarized light at 676.4 and 441.6 nm) the local efficiency in the center is relatively low. When the expanding beam covers the area with higher local efficiency the integral value reaches its maximum. For wider beams the integral efficiency decreases again.

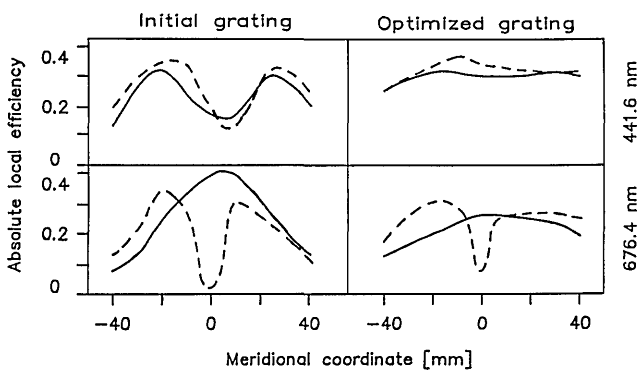

Fig. 2. Measured local efficiency on the meridional grating diameter at 441.6 and 676.4 nm for the initial and the optimized gratings for TE (solid curves) and TM (dashed curves) polarizations.

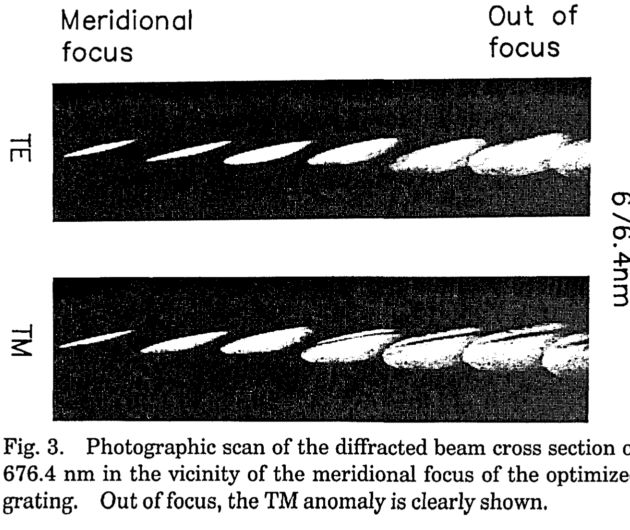

Fig. 3. Photographic scan of the diffracted beam cross section of 676.4 nm in the vicinity of the meridional focus of the optimized grating. Out of focus, the TM anomaly is clearly shown.

Table 1. 1/e Beam Diameter ϕ_B Generated on the Grating Surface by Micro Objectives With Different Magnifications

	Magnification						
Beam Diameter	0×	3.7×	8×	12.5×	25×	50×	100×
ϕ_B at 441.6 nm (mm)	0.5	3	5.5	6.5	11	19	50
ϕ_B at 676.4 nm (mm)	1	9	17	20	36	60	150

In most practical situations the grating is used for unpolarized light. The optimum relative beam diameter lies in the region 0.3–0.4. Lower values can ensure a small integral efficiency increase in anomaly-free situations but can lead to a significant efficiency decrease in regions with anomalies (and in any case the user loses resolution). Higher relative beam diameters cause an integral efficiency decrease and eventually the undesirable scattering of incident light outside the grating.

From an efficiency point of view, it is valuable to illuminate the grating by narrow beams (e.g., $\Phi_B/\Phi_G = 0.2$–0.3) in the blue region and by somewhat wider beams (e.g., $\Phi_B/\Phi_G = 0.3$–0.4) in the red region. Fortunately, such situations are realized in practice in a natural manner owing to the spectral dispersion of existing sources such as objectives, fibers, etc. So we have an accordance between optimization requirements and practical conditions. The dependence between illumination divergence and wavelength must be kept in mind when one predicts theoretically the spectral behavior of the integral efficiency by weighted summation (or integration) of local efficiency values. In the considerations presented above we have assumed a Gaussian illumination, which can be achieved by a micro objective or by a monomode fiber. In principle, similar conclusions can be drawn for sources that provide homogeneous illumination, e.g., multimode fibers at suitable excitation conditions.

Two differences can be observed between the properties of the initial and optimized gratings: (A) In the region where only TM polarization exhibits anomaly ($\lambda = 676.4$ nm), the difference between TE and TM efficiency values (and therefore the polarization sensitivity) is significantly reduced for the optimized grating. The maximum values for unpolarized illumination differ by not more than 2% absolute, which is not critical in this case. (B) In the region where both polarizations exhibit anomaly ($\lambda = 441.6$ nm), the efficiencies for both polarizations are practically identical and coincide with the values for unpolarized light. But the optimized grating is remarkably improved in comparison with the initial one—the total efficiency is increased by 5% absolute (from 20% to 25% at $\Phi_B/\Phi_G = 0.5$) and even 10% absolute (from 23% to 33% at $\Phi_B/\Phi_G = 0.2$). This is an important demonstration of the possible role of groove depth optimization in concave holographic grating design.

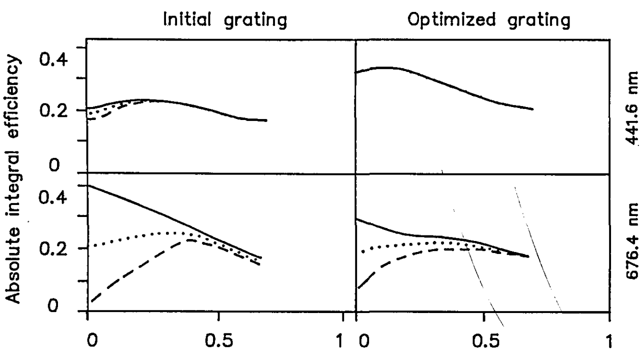

Fig. 4. Measured integral efficiency versus relative illuminating beam diameter at 441.6 and 676.4 nm for TE (solid curves) and TM (dashed curves) polarization and for unpolarized light (dotted curves) for the initial and the optimized gratings.

3. Conclusions

An experimental comparison is made between two concave spherical holographic gratings with identical recording geometries but with different exposure conditions and, consequently, with different radial groove depth distributions. The importance of the optimization of modulation distribution for improvement of grating efficiency is shown: in the blue spectral region (at 441.6 nm in our case) the absolute efficiency increase amounts to 5–10%, which is equal to a relative increase of 25–43%.

One important prediction from Ref. 1 was confirmed experimentally—that the grating efficiency can be improved not only by optimizing the grating itself (its radial groove depth distribution) but also by optimizing the illumination conditions.

When designing a concave grating, one must combine geometrical-optics considerations about the form of the focal curves and about the dimensions of the focal spots with a wave-optics analysis of local efficiency anomalies and of the radial modulation distribution in order to achieve the maximum possible integral efficiency over the entire operating spectral region.

Reference

1. E. G. Loewen, E. K. Popov, L. V. Tsonev, and J. Hoose, "Experimental study of local and integral efficiency behavior of a concave holographic diffraction grating," J. Opt. Soc. Am. A **7**, 1764–1769 (1990).