Optical characterization of ultra-high diffraction efficiency gratings

A. Bunkowski, O. Burmeister
Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Universität Hannover, Callinstr. 38, 30167 Hannover, Germany
alexander.bunkowski@aei.mpg.de

T. Clausnitzer, E.-B. Kley, and A. Tünnermann
Institut für Angewandte Physik, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany

K. Danzmann, and R. Schnabel
Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Universität Hannover, Callinstr. 38, 30167 Hannover, Germany

We report on the optical characterization of an ultra-high diffraction efficiency grating in 1st order Littrow configuration. The apparatus used was an optical cavity built from the grating under investigation and an additional high reflection mirror. Measurement of the cavity finesse provided precise information about the grating’s diffraction efficiency and its optical loss. We measured a finesse of 1580 from which we deduced a diffraction efficiency of (99.635±0.016)% and an overall optical loss due to scattering and absorption of just 0.185%. Such high quality gratings, including the tool used for their characterization, might apply for future gravitational wave detectors. For example the demonstrated cavity itself presents an all-reflective, low-loss Fabry-Perot resonator that might replace conventional arm cavities in advanced high power interferometers. © 2008 Optical Society of America

OCIS codes: 050.1950, 230.1360, 120.2230.

High quality optics are key devices in laser interferometric precision measurements. Especially for high power laser applications with nested cavities, such as in gravitational wave detectors, mirrors with high reflectivity and low overall optical loss are essential. Mirrors
with a power reflectance greater than 99.9998% for a given laser wavelength have been reported.\textsuperscript{2} The overall optical loss consisting of stray light from the surface, transmission, and absorption in the coating was as low as 1.6 ppm.\textsuperscript{2}

Gratings are traditionally used in applications where one wants to spatially resolve different optical wavelengths, e.g. in spectrographs or pulse compressors/stretchers for short pulse laser systems. In these applications high diffraction efficiency over a range of optical wavelengths is desired. Dielectric reflection gratings having diffraction efficiencies of 96\%, 97\%, and 99\% have been reported.\textsuperscript{3,4,5} However the measurement techniques used there only allowed for a rough estimation of the diffraction efficiency and no error bars for the values were given. Diffraction gratings may also be used in advanced high power laser interferometers,\textsuperscript{6,7} where they allow for the all-reflective realization of beam splitters and cavity couplers and therefore may help to reduce thermal effects in the substrate like thermal lensing\textsuperscript{8} and thermo-refractive noise.\textsuperscript{9} In interferometric applications monochromatic laser light is used and the wavelength dispersive property of the gratings is not essential. The point of interest lies in the number and the properties of the reflective diffraction ports and their couplings that determine the interference between input beams. Two different all-reflective resonator concepts have been demonstrated to date. High efficiency gratings in first-order Littrow configuration form cavity couplers with two ports analogous to partially transmitting mirrors.\textsuperscript{7} Low efficiency gratings in second-order Littrow configuration can be used as low-loss couplers with three ports.\textsuperscript{10} Analogous to conventional mirrors however, optical loss in terms of scattering or absorption has to be minimized in order to gain maximum laser power build-up and measurement sensitivity. The question therefore arises if high-efficiency gratings with highly corrugated surfaces will ever be able to fulfill the strict low scattering loss requirements.

In this article we report on the optical characterization of a high efficiency grating in view of applications in interferometry. The grating was used in first-order Littrow configuration to couple laser light into a Fabry-Perot cavity with a measured finesse of 1580 ± 60. This experiment allowed for the accurate measurement of both the grating’s loss and the diffraction efficiency. The latter one was determined to be (99.635 ± 0.016)%. To our knowledge this is the highest and most accurately determined value reported in the literature.

The grating device was designed for a laser wavelength of 1064 nm and a Littrow angle of approximately 30°. The grating structure had rectangular grooves with a period of 1060 nm. For fabrication we used electron beam direct writing (electron beam writer LION LV1 from Leica Microsystems Jena GmbH) and reactive ion beam etching into the top layer of a highly reflective dielectric multilayer stack. The stack consisted of 36 alternating layers of 195 nm SiO\textsubscript{2} and 136 nm Ta\textsubscript{2}O\textsubscript{5} placed on a fused silica substrate with a surface flatness of λ/10. For the theoretical optimization of the grating we used the rigorous coupled wave analysis.\textsuperscript{11}
In order to ensure a good reproducibility and homogeneity over the whole grating area an important concern of the design was a large groove parameter tolerance of the diffraction efficiency. By using SiO$_2$ with a thickness of 1.12 $\mu$m as the top layer of the dielectric stack the theoretical design exhibited a diffraction efficiency of more than 99% for groove depths between 700 nm and 850 nm and groove widths between 530 nm and 760 nm.

A schematic of our experiment is seen in Fig. 1. The light source used was a 1.2 W diode pumped Nd:YAG laser at 1064 nm (Model Mephisto from Innolight GmbH). Before the s-polarized laser beam was sent into the grating cavity it was spatially filtered with a triangular ring cavity (mode cleaner). The highly reflective end mirror of the grating cavity was mounted on a piezoelectric transducer (PZT) which was used to either scan or to actively control the cavity length. The error signal for the electronic servo loop was obtained from the cavity transmission demodulated at the phase modulation frequency introduced by the EOM.

In first order Littrow configuration only two diffraction orders exist and the grating (subscript 1) is characterized by the zeroth and first order amplitude diffraction efficiencies $r_1$ and $\eta_1$, respectively, as well as the loss amplitude $l_1$. Similarly the cavity end mirror (subscript 2) is described by $r_2$, $t_2$ and $l_2$. Energy conservation implies

\[ r_1^2 + \eta_1^2 + l_1^2 = 1, \quad (1) \]
\[ r_2^2 + t_2^2 + l_2^2 = 1. \quad (2) \]

Figure 2 shows the transmission spectrum of the cavity as the PZT is linearly scanned over one free spectral range of the cavity. In addition to the peaks of the fundamental mode
of the cavity there are only two smaller peaks from higher order modes visible indicating a good matching of laser beam and cavity mode.

A method to obtain a precise value for a mirror reflectance close to unity is a measurement of the finesse $F$ of a cavity consisting of a mirror with known reflectance and the one in question. For the first time we applied this method to characterize a high efficiency grating. If losses due to absorption in the space between the mirrors (which would appear additionally to $l_1$ and $l_2$) are neglected the finesse $F$ of a two mirror Fabry-Perot resonator depends on the reflectance of the two end mirrors only. In our case one of the end mirrors is a grating and the finesse can be approximated by

$$F = \pi (\eta_1 r_2)^{1/2} / (1 - \eta_1 r_2).$$

(3)

For a cavity of length $L$ its free spectral range is given by $f_{\text{FSR}} = c/2L$ where $c$ is the speed of light. The ratio of $f_{\text{FSR}}$ to the full width at half maximum $f_{\text{FWHM}}$ of the Airy transmission spectrum peaks determines the finesse

$$F = f_{\text{FSR}} / f_{\text{FWHM}}.$$  

(4)

The length of the cavity was measured to $L = (94 \pm 1)$ mm, resulting in $f_{\text{FSR}} \approx 1.6$ GHz. The cavity linewidth was measured utilizing frequency marker signals. The laser light was phase modulated at $f_{\text{mod}} = 4$ MHz using an electro optical modulator (EOM). The AC output of the photodiode in front of the grating cavity was then demodulated at $f_{\text{mod}}$. For the correct demodulation phase this signal shows a minimum and a maximum at exactly $\pm f_{\text{mod}}$ and can be used to calibrate the x-axis in Fig. 3. The figure shows a typical measured DC signal of the photo diode behind the cavity as well as the marker signals at $f_{\text{marker}} = \pm (4 \pm 0.04)$ MHz.
Fig. 3. Scan over one cavity transmission peak. The x-axis was calibrated with ±4MHz marker signals.

while the cavity was linearly scanned with 1kHz repetition rate. The uncertainty in the position of the marker signal is due to an error in the demodulation phase. A fit of the transmission signal to the well known Airy function of cavities permitted the calculation of the width of the transmission peak. Due to nonlinearities in the piezoelectric transducer and acoustic vibrations there is a statistical variation of the linewidth of the peak. We averaged over 75 measurement using different operating points of the piezoelectric transducer and could reduce the statistical error in the peak width to ±3.5%.

With Eq. 4 we could calculate the finesse of the cavity \( F = 1580 ± 60 \). The cavity end mirror was super-polished and coated by REO (Research Electro-Optics, Inc) and specified to have values of \( t_2^2 = 300 ± 30 \) ppm and \( b_2^2 < 30 \) ppm. From these specifications we estimate the mirror’s reflectivity to \( r_2^2 = (99.9685 ± 0.0034)\% \). With Eqs. 2 and 3 we obtained \( \eta_1^2 = (99.635 ± 0.016)\% \) for the grating’s 1st order diffraction efficiency. The error in \( \eta_1^2 \) results from an error propagation of each known uncertainty of the quantities \( L, f_{\text{marker}}, \) fitted peak width and \( r_2^2 \) as shown in table 1.

The specular reflection of the grating was measured independently with a calibrated power meter to be \( r_1^2 = (0.18 ± 0.009)\% \). Hence we calculated the overall loss of the grating according to Eq. 1 to be \( l_1^1 = (0.185 ± 0.025)\% \). We emphasize that this loss contained all contributions from scattering, absorption, transmission, and higher diffraction orders. To our best knowledge this result presents the lowest and most accurately determined grating loss reported in the literature. Previous results were those by Perry et al.\(^3\) and Hehl et al.\(^4\) who reported 1.5% and 1 - 2% loss, respectively. Destouches et. al\(^5\) have not commented on the loss.
Table 1. Error propagation

| Quantity     | error     | proj. error for $\eta_2^2$ [ppm] |
|--------------|-----------|----------------------------------|
| L            | ±1 mm     | ±48                              |
| $f_{\text{marker}}$ | ±40 kHz  | ±43                              |
| peak width   | ±3.5%     | ±143                             |
| $r_2^2$      | ±34 ppm   | ±34                              |
| Total RMS error expected |          | ±160                             |

In addition to the grating’s loss we also investigated its influence on the laser beam’s spatial profile. Again a cavity in first order Littrow configuration was set up with cavity mode waist on the gratings surface now using an end mirror with power reflectivity $r_2^2 = 99\%$ to reduce the finesse value and to increase transmission. The cavity length was locked to one of the transmission maxima using the radiofrequency phase-modulation technique described above. The beam profile for the horizontal and vertical directions were measured after the cavity using a seven-blade tomographic profiler (SuperBeamAlyzer from Melles Griot) and fitted with a Gaussian model, as shown in Fig. 4. The sum of the absolute differences between the value of every measured point and the fitted function divided by the sum of the values of all fitted points is a measure of how much beam power can be represented by a gaussian function. For both directions we obtained values of greater than 99%. For this experiment the modecleaner had been taken out which allowed us to observe a modecleaning effect from the grating cavity. We characterized the laser beam behind the EOM using the same apparatus and got spatial profiles that were described by a gaussian function by only 98%.

In summary we presented a detailed characterization of diffraction efficiency and overall loss of a grating in 1st order Littrow mount. The grating’s diffraction efficiency showed an outstanding high value which enabled the construction of a high finesse cavity as a characterizing tool. The value of the finesse was limited by the first order diffraction efficiency. This is in contrast to Ref. 10 where a low diffraction efficiency grating was characterized with a high finesse cavity and where the limit for the finesse was given by the specular reflectivity of the grating. Our approach is a valuable diagnostic tool to improve future techniques of grating fabrication, since all types of loss are simultaneously detected. We expect that with improved technology high grating efficiencies with simultaneously low loss are possible that even fulfill the strict requirements of future interferometers such those for gravitational wave detection.

This work was supported by the Deutsche Forschungsgemeinschaft within the Sonder-
Fig. 4. Spatial beam profile of the laser beam after the cavity for horizontal (perpendicular to the grating lines) and vertical (parallel to the grating lines) direction. Top: measured points (dots) and best gaussian fit (solid line); Bottom: Residuals between measurement and fit.

References

1. B. Abbott et al., Nuclear Instruments and Methods in Physics Research A 517, 154 (2004).
2. G. Rempe, R. J. Thompson, H. J. Kimble, and R. Lalezari, Opt. Lett. 17, 363 (1992).
3. M. D. Perry, R. D. Boyd, J. A. Britten, D. Decker, B. W. Shore, C. Shannon, and E. Shults, Opt. Lett. 20, 940 (1995).
4. K. Hehl, J. Bischoff, U. Mohaupt, M. Palme, and B. Schnabel, Appl. Opt. 38, 6257 (1999).
5. N. Destouches, A. V. Tishchenko, J. C. Pommier, S. Reynaud, O. Parriaux, S. Tonchev, and M. Abdou Ahmed, Opt. Expr. 13, 3230 (2005).
6. R. W. P. Drever, in Proceedings of the Seventh Marcel Grossman Meeting on General Relativity, M. Keiser and R.T. Jantzen, eds. (World Scientific, Singapore, 1995).
7. K.-X. Sun and R.L. Byer, Opt. Lett. 23, 567 (1997).
8. W. Winkler, K. Danzmann, A. Rüdiger, and R. Schilling, Phys. Rev. A 44, 7022 (1991).
9. V. B. Braginsky, M. L. Gorodetsky, and S. P. Vyatchanin, Phys. Lett. A 271, 303 (2000).
10. A. Bunkowski, O. Burmeister, P. Beyersdorf, K. Danzmann, R. Schnabel, T. Clausnitzer, E.-B. Kley, and A. Tünnermann, Opt. Lett. 29, 2342 (2004).
11. M. G. Moharam, and T. K. Gaylord, J. Opt. Soc. Am. 72, 1385 (1982).
12. B. Willke, N. Uehara, E. K. Gustafson, R. L. Byer, P. J. King, S. U. Seel, and R. L. Savage, Jr., Opt. Lett. 23, 1704 (1998).