Volume phase gratings for spectroscopy, ultrafast laser compressors, and wavelength division multiplexing

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ABSTRACT

Volume phase (VP) gratings are now available and being applied to the applications of astronomical spectroscopy, Raman spectroscopy, ultrafast lasers, and wavelength division multiplexers (WDMs). A volume phase grating results from the recording of an interferometric pattern within the volume of a material which, when suitably processed, becomes a modulation of the material's index of refraction. When a VP grating is subsequently illuminated, the light interacts with the material due to the recorded pattern. Light propagates within and out of the VP grating according to Bragg diffraction.

Definitions of various VP gratings designed and fabricated to study performance are provided as relating to the applications listed above. Performance parameters include diffraction efficiency, spectral coverage, and angular coverage. Descriptions of the test methods are given. Performance data is provided and compared to the respective design.

Keywords: Volume phase grating, VP grating, VPH grating, holographic grating, spectroscopy, wavelength division multiplexer, WDM

1. INTRODUCTION

Technology developments of holographic materials, processes, and analysis tools in the 1960s\textsuperscript{1} and 1970s\textsuperscript{2,3} gave rise to an industry which fabricates high quality, high value holographic optical elements for the defense sector. Manufacturing techniques have been refined over the years and with a resurgence of development activity, holographic elements are economically viable for scientific and commercial applications. One such successful product based on this technology is the Holographic Notch Filter\textsuperscript{4,5}. This filter offers high rejection (greater than an optical density of six) coupled with narrow spectral bandwidth (less than 350 wavenumbers) and has revolutionized Raman spectroscopy\textsuperscript{6}.

A related holographic element, the volume phase (VP) grating\textsuperscript{7}, is now available to add design flexibility and performance improvements to those applications requiring dispersing optics. VP gratings differ from classical surface-relief gratings in that diffraction is accomplished not by interaction of light with a surface structure but with a grating recorded in a thin film encapsulated between two plates of glass. A major difference between surface-relief gratings and VP gratings is the mechanism by which diffraction takes place. Light that impinges on a surface-relief grating interacts with the abrupt changes in surface profile resulting in constructive and destructive interference for particular combinations of angles and wavelengths. The depth of the profile is on the order of a wavelength of light or less.\textsuperscript{8} The structure of a volume phase grating is a generally sinusoidal modulation of the index of refraction and recorded in a film of thickness from a few to well over one hundred microns. This is a “thick” grating and thus causes the efficiency profile of the imaged light to be governed by Bragg diffraction.

A material known for its ability to provide high modulation of the index of refraction, low absorption through the visible and near infrared, and low scattering is dichromated gelatin (DCG)\textsuperscript{9}. All of the VP gratings in this report are fabricated in DCG.

Among the unique and desirable properties of VP gratings are:
- Encapsulation between two glass substrates provides environmental protection.
- The volume phase grating can be easily handled and cleaned using common optical cleaning materials.

\textsuperscript{*} Operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.
• Anti-reflection coatings can be applied to the outer surfaces to minimize reflections and maximize throughput.
• The holographic material when properly encapsulated (as between two glass substrates) can have a very long lifetime.
• Low polarization sensitivities are possible with low and high dispersion transmission gratings.
• Each manufactured grating is an optically recorded original. There are no replication errors.
• Theoretical diffraction efficiencies can approach 100% for high line frequencies (600 to 6000 l/mm).
• Mature manufacturing processes are capable of producing gratings that approach the theoretical design parameters.
• Complex grating structures can be produced to accommodate optical constraints or improve optical performance.
• Current technology allows grating sizes in excess of 500 mm.
• Volume phase gratings can be produced in either transmission or reflection mode.

A brief discussion of the principals of designing and fabricating a volume phase grating is presented. Results of grating performance tests at the final stage of manufacture are given. Manufacturing results of astronomical gratings are compared to those obtained through an independent set of tests performed at an installation site.

2. VOLUME PHASE HOLOGRAPHIC GRATINGS

2.1 Constructing a volume phase holographic grating

A volume phase (VP) holographic grating results from optically recording a suitable microscopic pattern in a film of photosensitive material. The output from a laser is split into two beams. These beams are expanded and collimated before directed to pass through one another. The light produces an interference pattern in the space shared by both beams. This pattern is a series of parallel planes whose spacing is determined by the angle between the two beams and the wavelength of the light. The optical system is constructed to preserve spatial and temporal coherence and to remain stationary for adequately long periods. This is a holographic exposure system. A glass substrate coated with the photosensitive film is set where the interference pattern is generated and exposed. The film responds to the exposure by a change in density in the regions where there was constructive interference (a bright interference fringe). This change in density causes a slight variation or modulation in the index of refraction in the material. The exposed film is chemically processed to amplify the density variations hence producing an enhanced modulation in the index of refraction. Careful process controls can result in a faithful reproduction of the original interference pattern in the material. After the grating has been processed to obtain high efficiency, it is laminated to a glass cover. This cover serves as a potential carrier for an anti-reflection (AR) coating or as a substrate onto which prisms may be additionally attached and as protection from the environment. Figure 1 shows the final configuration of a simple volume phase grating (no optional prisms attached).

![Figure 1. Configuration of an Assembled VP Grating](image)

2.2 Volume phase grating fundamentals

As is the case for a surface-relief grating a VP grating images according to the grating equation

\[ m \cdot \nu \cdot \lambda = \sin(\theta_{\text{Incident}}) - \sin(\theta_{\text{Diffracted}}) \]  

(1)

where \( m \) is the order of diffraction, \( \nu \) is the grating frequency, \( \lambda \) is the wavelength of the incident light in free space, \( \theta_{\text{Incident}} \) is the angle of incidence in air, and \( \theta_{\text{Diffracted}} \) is the angle of the diffracted light in air. For a given wavelength and incident angle...
Equation 1 allows us to find the angle of the diffracted light for any particular order. A VP grating has the added dimension of depth, and the efficiency with which the light energy is diffracted is determined by Bragg effects. Because the grating has depth, the fringe planes have an additional degree of freedom in that they may be slanted. The fringe period $\Lambda$, measured perpendicular to the fringe planes, is less than the period $\Lambda_s$ of the surface grating formed by the intersection of the fringe planes with the grating surface. In Equation 1, the grating frequency $\nu$ is the surface grating frequency, so that $\nu = 1/\Lambda_s$. In the special, but common, case of fringes that are orthogonal to the grating surface, $\Lambda = \Lambda_s$.

For a transmission grating with orthogonal fringes, the Bragg condition is given by

$$m_B \cdot \lambda = 2 \cdot \Lambda \sin(\theta_{\text{Incident}})$$  

(2)

where $m_B$ is an integer that represents the Bragg order. When the Bragg condition (2) is satisfied, $\theta_{\text{Diffracted}}$ and $\theta_{\text{Incident}}$ make equal and opposite angles with the fringe planes. The terms “Bragg wavelength” and “Bragg angle” are commonly used to describe the wavelength and angle that exactly satisfy the Bragg condition. In reality there is an envelope about the Bragg wavelength and Bragg angle in which there is significant diffracted light energy, giving rise to a spectral bandwidth and angular bandwidth for the VP grating.

![Figure 2](image)

**Figure 2. Light path at Bragg condition through a transmission VP grating having orthogonal fringes**

### 2.3 Approaches to grating design and analysis

Various approaches are used to design and analyze the performance of a volume phase grating. A well known coupled-wave analysis developed by Kogelnik\textsuperscript{10} assumes only zero and first order propagation by a grating constructed in a thick film. From this analysis the diffraction efficiency $\eta_s$ of s-polarized light at the first order Bragg condition of an orthogonal grating is given by

$$\eta_s = \sin^2 \left( \frac{\pi \cdot \Delta n \cdot d}{\lambda \cdot \cos \alpha} \right)$$  

(3)

where $\Delta n$ is the modulation in refractive index of the recording material, $d$ is the thickness of the film, $\lambda$ is the freespace wavelength, and $\alpha$ is the angle of incidence inside the material. As can be seen by Equation 3 the efficiency with which a volume grating diffracts light is dependant not only on the incidence angle but also on the physical attributes of index modulation and film thickness. The efficiency for p-polarized incident light is modified by a cosine factor given by

$$\eta_p = \eta_s \cdot \cos(\theta_{\text{Incident}} - \theta_{\text{Diffracted}})$$  

(4)

where $\theta_{\text{Incident}}$ and $\theta_{\text{Diffracted}}$ are angles inside the grating material. It can be seen there is strong polarization dependence when the argument of the cosine is near 90 degrees. While this approach is simple it provides very good approximations within the scope of the assumptions made at the onset of the analysis.
A more thorough description of VP grating performance is provided through either modal analysis\textsuperscript{11} or rigorous coupled-wave analysis (RCWA)\textsuperscript{12, 13}. Each method provides exact and equivalent solutions\textsuperscript{14}. The input parameters remain the same as for the simple coupled-wave analysis given above. These analysis techniques provide solutions for multiple order propagation, simultaneous transmission and reflection orders, and more extreme configurations. The design and performance estimates provided later were generated using rigorous coupled-wave analysis.

2.4 Designing a VP grating

Designing a volume phase grating for a given application involves optimizing predicted performance based on the variables available during the fabrication process. These variables are the angles of the two exposing beams, angle of the bisector of the two exposing beams, film thickness, wavelength of exposure, and modulation of the index of refraction. The angles of the two exposing beams and the angle of the bisector of the two beams determine the grating frequency and the fringe plane angle with respect to the film’s surface. The modulation of the index of refraction is influenced by several factors of the production process. Film hardness, film resilience, film sensitivity to light, level of exposure, stability of the holographic exposure system during exposure, processing temperature, and processing agitation level are a few of the manufacturing steps which determine the index modulation available. Design tolerances determine the level of control required on the manufacturing process.

2.5 Testing a VP grating

Measurement techniques vary. At KOSI, where VP gratings are manufactured, several lasers are used providing various wavelengths throughout the visible and into the near infrared. Measurements are made with a chopped beam to isolate the signals from ambient sources. NOAO uses a monochrometer illuminated with a stabilized quartz lamp as a light source. Diffraction efficiency is determined by calculating the ratio of the light diffracted into the order of interest verses the light incident on the grating.

3. ASTRONOMICAL GRATINGS

3.1 Grating definitions

In a collaborative arrangement between Kaiser Optical Systems, Inc. (KOSI) and National Optical Astronomy Observatories (NOAO), funded by a grant from the National Science Foundation, several gratings have been constructed by KOSI and tested by NOAO. Table 1 lists the gratings, the peak wavelengths for first order diffraction, and their respective grating frequencies.

<table>
<thead>
<tr>
<th>Grating</th>
<th>First Order Peak Wavelength (nm)</th>
<th>Grating Frequency (line pairs /mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HG-T-1064-9</td>
<td>1064</td>
<td>300</td>
</tr>
<tr>
<td>HG-T-532-19</td>
<td>532</td>
<td>1200</td>
</tr>
<tr>
<td>HG-T-532-40</td>
<td>532</td>
<td>2400</td>
</tr>
<tr>
<td>HPG-656/486-23</td>
<td>656 and 486</td>
<td>1200 and 1620</td>
</tr>
</tbody>
</table>

Table 1. Grating Definitions and Status

The first three gratings on the list are simple transmission gratings with peak wavelength in first order coinciding with emission lines of common lasers. These wavelengths were chosen to facilitate measurements.

Grating HPG-656/486-23 is an assembly containing two individual gratings laminated to each other. This arrangement generates two separate Bragg envelopes covering different regions of the spectrum. In particular, the peak wavelength of the first order of each grating was selected to coincide with one of the H\textalpha\ and H\textbeta\ emission lines yet allow the other line to pass undiffracted.
3.2 Designs

Figures 3 through 6 show the performance predicted by rigorous coupled-wave analysis for gratings described in Table 1.

**Figure 3.**

**Figure 4.**

**Figure 5.**
3.3 Test results

Figures 7 through 10 show the diffraction efficiency verses wavelength measurements of the gratings for which design predictions are given in Section 3.2 above.

The data collected for HG-T-532-19 by KOSI and presented in Figure 8 was taken with the grating angle adjusted away from 18.6 degrees to the respective Bragg angle for each of the measurement wavelengths. This demonstrates the tunable nature of a VP grating to obtain high efficiency at wavelengths other than at the design peak.
Figure 8.
Unpolarized light incident at 18.6 degrees.

Figure 9.
Light polarized as indicated and incident at
39.7 degrees.

Figure 10.
Unpolarized light incident at 40 degrees.
3.4 Angular bandwidth

The angular bandwidth of the VP gratings (with the exception of HG-T-1064-9) was measured at various laser wavelengths. Each bandwidth is centered about the Bragg angle for the respective wavelength. The results are given in Table 2 below.

<table>
<thead>
<tr>
<th>Grating</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>457</td>
</tr>
<tr>
<td>HG-T-532-19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
</tr>
<tr>
<td>HPG-656-23</td>
<td></td>
</tr>
<tr>
<td>Component only</td>
<td></td>
</tr>
<tr>
<td>HPG-486-23</td>
<td></td>
</tr>
<tr>
<td>Component only</td>
<td>7.5</td>
</tr>
<tr>
<td>HG-T-532-40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 2. Measured angular bandwidths (in degrees).

3.5 Observations on measured data with respect to the predicted curves

In general there is good correlation between the measured data and what was predicted by the rigorous coupled-wave analysis. One of the more notable deviations between the predicted and measured performance is seen in the 300 l/mm grating, HG-T-1064-9. It is interesting to note that while the first order failed to achieve the expected 85% diffraction efficiency at 1064 nm the VP grating has increased performance in the third order. Here it is still rising above 55% at 375 nm where the design predicts only 47%.

4. GRATINGS FOR ULTRAFAST LASERS

4.1 Gratings used as pulse compressors

Ultrafast lasers achieve pulsewidths on the order of femtoseconds ($10^{-15}$ seconds). One technique used to achieve very short pulses with high power is chirped pulse amplification (CPA). The principle of CPA is to stretch the light pulse in the time domain before it enters an optical amplifier. Then, once amplified, the pulse is compressed, returning it to (nearly) the same pulsewidth as before it was stretched. Dispersion elements are used as the stretching and compression optics. Volume phase gratings have excellent performance in pulse compression. They can have very high diffraction efficiencies as evident by measured performance shown in Figures 11 and 12 below, they have high damage thresholds, and the configuration also aids in alignment of the gratings to optimize performance.

4.2 Grating predicted performance and test results

![Figure 11](#)

Figure 11. RCWA Predicted and measured performance of HG-T-775-44-100 (1800 l/mm). Polarized ‘s’ light incident at 44.2 degrees.
4.3 Observations on performance of pulse compression VP gratings

Very high efficiencies can be expected and are obtained from VP gratings. The two examples show the measured efficiency is within 1% of that predicted by rigorous coupled-wave analysis.

5. TELECOMMUNICATION GRATINGS

5.1 Grism definition

The telecommunication industry uses wavelength division multiplexers (WDM) and optical spectrum analyzers (OSA) in fiber optic based communication systems. These devices need to differentiate one channel from several transmitted down a fiber. One approach is to use a dispersion element such as a volume phase grating. The grating described here has a center wavelength of 1550 nm and a spectral operating range from 1525 to 1565 nm. The VP grating is sandwiched between two prisms in order to achieve the high dispersion necessary to separate signals of closely spaced channels. Packaging considerations requires the light path through the grism be such that the center wavelength after diffraction travels parallel to but in the opposite direction of the input. See Figure 13 below.

This configuration allows for the very high angle of incidence on the grating necessary to satisfy the Bragg condition for 1550 nm center wavelength and 1852 l/mm grating frequency. The element disperses up to 0.67°/nm at the high wavelength end of its spectral bandwidth. Polarization independent response can be a critical requirement of a WDM or OSA element. The element described here is optimized for insensitivity to polarization with diffraction efficiency is traded for nearly equivalent ‘s’ and ‘p’ polarization response.
5.2 Grism predicted performance and test results

Figure 14 shows the efficiency vs. wavelength performance predicted by RCWA for the OSA grism described above. The test results added to this chart demonstrate the close fit over the spectral range for both ‘s’ and ‘p’ polarization states.

![Figure 14](image)

6. OBSERVATIONS AND CONCLUSIONS

The results presented in this paper demonstrate volume phase gratings are valuable tools for the optical designer and engineer. Three application areas are highlighted: astronomy, ultrafast lasers, and telecommunications. VP gratings have great practical advantages as well as comparable or superior performance characteristics with regard to diffraction efficiency, polarization independent response, and to other dispersion optics.

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