Gratings with Integral Calibration Features

LightSmyth introduces a new grating product based on advanced design and fabrication methods. The new product comprises a single substrate with a primary grating and an array of sub-millimeter alignment/calibration gratings. The alignment/calibration gratings produce multiple signals that, when viewed in a focal plane detection region, provide for precise focusing, wavefront adjustment, and multi-point spectral calibration using a single reference wavelength.

A grating with integral alignment/calibration features is shown schematically in Figure 1. The primary grating functions in the traditional manner. The Calibration Grating Array comprises a number of small gratings (typically 0.5×2 mm). In the Figure, 12 small gratings are shown. Each small grating has an individually determined period. The lines of the small gratings may also be tilted by individually determined amounts relative to the lines of the primary grating. The Calibration Grating Array is positioned with interferometric accuracy relative to the primary grating. In fact the entire grating (primary and Calibration Array) is fabricated in a single step.

LightSmyth self-calibrating gratings come in two basic varieties differentiated by the orientations of the lines in the Calibration Array gratings. If the lines of the Calibration Array gratings and the Primary grating are parallel, the output of the Primary Grating and all of the Alignment/Calibration gratings fall along a single line in the gratings detection plane. Thus the calibration signals can be utilized in systems employing a one-dimensional detector array. When not in use for calibration, the Calibration Array would typically be blocked by a shutter or other device to prevent signals from the Array from interfering with spectra of interest.

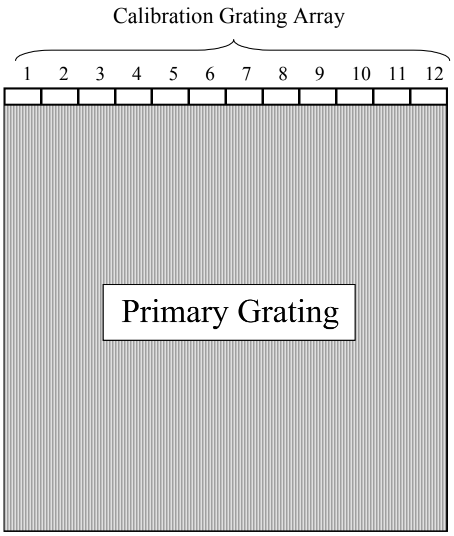

Figure 1. Schematic of a Grating with integral calibration features.

When the lines of the Calibration Array gratings are tilted in carefully designed amounts, the alignment/calibration signals produced may be made to fall along one or more lines parallel to the dispersion line of the primary grating so that a second linear detector array or a two-dimensional detection array can utilize the alignment/calibration signals and the alignment/calibration signals do not interfere with the primary grating output. Thus there is no need to screen a tilted-line Calibration Array when spectra are taken.

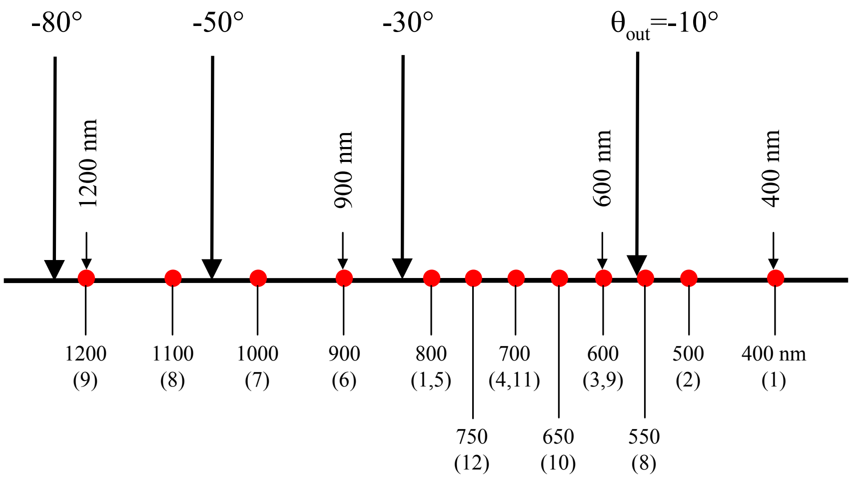

Figure 2. Schematic depiction of detection plane showing Primary Grating dispersion line and Calibration Array markers in the case where Primary and alignment/calibration grating lines are parallel.

In Figure 2, we schematically depict the detection plane of a grating configured after Figure 1 with a non-tilted Calibration Array. The properties of the primary and alignment/calibration gratings are given in Table I. The output pattern of Figure 2 results when incident light strikes the grating at 30^o from the normal (perpendicular to the primary grating lines). The angles shown at the top of Figure 2 refer to the direction output signals travel relative to the substrate normal with minus signs indicating that input and output are on the same side of the normal. The horizontal line is the dispersion line of the Primary Grating in a detection plane. The wavelength numbers above the horizontal line are given by the grating equation for the Primary Grating. The self-calibration and alignment features are shown as red circles. These marks are produced by illuminating the Calibration Array with a HeHe laser propagating along the standard input direction. Note that marker spots occur at precisely determined intervals along the primary grating dispersion line allowing for calibration of the detector scale with a single source regardless of spectral region. The wavelengths given below the horizontal line indicate the wavelength that the Primary Grating diffracts to the location of the calibration marks. The number in parenthesis indicates which grating in the Calibration Array produces each signal. It will be noted that some marker dots receive signal from two alignment/calibration gratings. These spots overlap when the input wavefront is uniform and focusing to the detection plane is correct. Otherwise, two marker spots appear providing an indicator for system alignment. It is vital to note that the calibration values shown below the horizontal line do not change as the angle of the input signal relative to the normal is changed. The calibration values are invariant unless the wavelength of the reference light source is changed. The invariance of the markers under changes in input and output angles is a powerful feature of the Calibration Array. For different input angles, the detection plane pattern would change, but each marker point visible will always remain correlated with the same Primary Grating output wavelength.

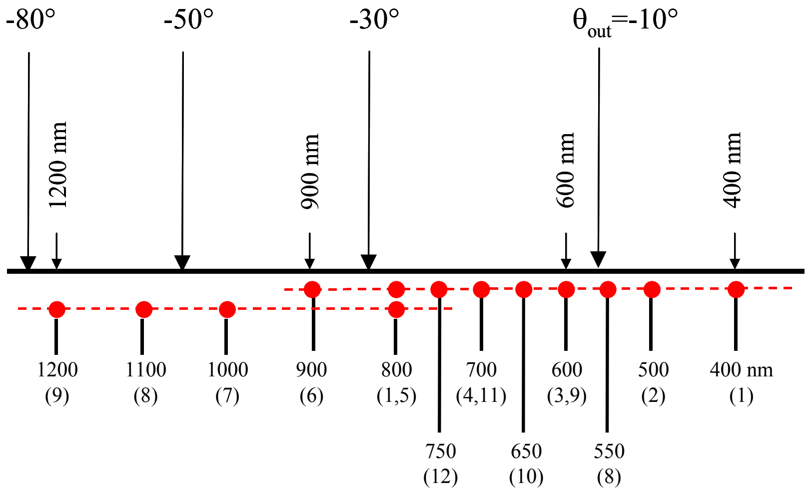

Figure 3. Schematic depiction of detection plane showing Primary Grating dispersion line and Calibration Array markers in the case where Primary and alignment/calibration grating lines are tilted.

A representative output pattern produced by a Calibration Array with tilted lines (see specifications in Table 1) is shown in Figure 3. The parameters shown in the Figure are similar to those of Figure 2. Note, however, that the marker dots now fall along two lines parallel to the dispersion line of the primary grating (horizontal solid line). A two-dimensional detector and a HeNe laser may be employed to fully calibrate the Primary Grating’s dispersion line. Other reference light sources may be employed as well, but the reference numbers given below the dispersion line will change. The tilt of the Calibration Array grating lines and the resulting displacement of marker dots away from the Primary Grating dispersion line eliminates cross talk and thus the need to screen the Calibration Array during spectral measurement. Note that the vertical separation between the reference markers and the Primary Grating dispersion line is enlarged for clarity. Typically the separation is set by an angular offset factor of a few degrees and the focal length of the focusing elements employed.

Table I				
Grating	First-order Marker wavelength* (nm)	Lines/mm (non-tilted)	Lines/mm (tilted)	Tilt angle (deg)
Primary	na	1200	1200	0
1	400	758.6	760.6	4.158
2	500	948.2	949.8	3.329
3	600	1137.7	1139.1	2.775
4	700	1327.4	1328.6	2.379
5	800	1517.2	1518.2	2.082
6	900	1706.7	1707.6	1.851
7	500	948.2	949.8	3.329
8	550	1043.0	1044.4	3.025
9	600	1137.7	1139.1	2.775
10	650	1232.6	1233.9	2.560
11	700	1327.4	1328.6	2.379
12	750	1422.2	1423.3	2.219

* First-order marker wavelength is the wavelength of light diffracted from the primary grating which falls at the same output angle as the HeNe marker signal from the referenced alignment/calibration grating. Note that alignment/calibration gratings produce additional HeNe markers at higher orders and that the marker wavelength is simply multiplied by the order number.

Technical notes on the analysis of gratings with tilted lines

The grating comprises a surface (taken for simplicity as lying in the xy plane) whose complex surface reflectivity (complex here means including amplitude and phase changes) undergoes periodic variation. The normal to the grating surface is **N** which in this case is parallel to **z**. The reflectivity can vary in amplitude, phase, or both. We refer to regions of constant reflectivity as diffractive contours which are typically simple straight lines.

Each grating possesses a wavevector $\mathbf{K_g}$ which lies in the grating plane and is oriented normal to the diffractive contours. The magnitude of $\mathbf{K_g}$ is 1/a, where, a, is the spacing between contours measured along a mutual normal.

Monochromatic light, of wavelength λ, incident on the grating from some location may be assigned a wavevector $\mathbf{k_{in}}$ oriented along its wavefront normal. The wavevector $\mathbf{k_{in}}$ has the magnitude $1/\lambda$. When the input light has a range of spectral components, wavevectors having different magnitudes may be chosen to represent the various color components.

In the simple case where $\mathbf{K_g}$, $\mathbf{k_{in}}$, and **N** lie in a plane, input and output directions, and wavelength are related according to the equation:

$$m\lambda = a\sin\theta_{in} - a\sin\theta_{out} \quad , \qquad \text{Eq. 1}$$

where m is any integer including zero which provides real solutions for the output angle. Since the wavelength of the incident light is involved in Eq. 1 for solutions with m≠0, the output angle will vary with input wavelength.

In more general cases, the output wavevector may be determined by decomposing the input wavevector into two parts, one in the plane of the grating and one perpendicular to it. These components are denoted $\vec{\mathbf{k}}_{in}^{p}$ and k_{in}^{z}, respectively. Analogous components for the output wavevector are $\vec{\mathbf{k}}_{out}^{p}$ and

$$\vec{\mathbf{k}}_{out}^{p} = \vec{\mathbf{k}}_{in}^{p} + m\vec{\mathbf{K}}_{g}; \qquad \text{Eq. 2a}$$

k_{out}^{z} . The allowed values of these quantities are given by the following equations:

$$k_{out}^{z} = \sqrt{\left(k_{in}^{2} - k_{out}^{p\ 2}\right)}. \qquad \text{Eq. 2b}$$

Here m is any integer including zero that provides for a real value of k_{out}^{z}. Eq 2 indicates that a single input beam generates one or more output beams and except for the beam corresponding to m=0, the output directions are color dependent. The m=0 beam is the specular reflection that one expects from any smooth dielectric or metallic surfaces and is not directionally controlled by the diffractive structure. The number of output beams is determined by the magnitude and orientation of $\vec{\mathbf{K}}_{g}$ relative to $\vec{\mathbf{k}}_{in}^{p}$. Eq. 2 can be employed determine the performance properties of LightSmyth diffraction gratings with integral calibration features when the alignment/calibration gratings are tilted relative to the Primary Grating.