Abstract—We present a series of aspherical lenses and diffraction gratings 3D printed for use as optical components in terahertz spectroscopy systems. Commercially available plastics for 3D printing (VisyJet Crystal, Acrylonitrile Butadiene Styrene (ABS) Plastic and acrylic based polymers) have also been characterized via Terahertz Time Domain Spectroscopy (TDS) and two-color wave photomixing. In addition, characterization has been achieved using synchrotron radiation at the Australian Centre for Synchrotron Science. The lenses were found to have a focal length of (35±2) mm suggesting high spatial resolutions might be achieved. This result agrees with the calculated focal length of 35.5 mm. Control over output maxima and beam splitting of the diffraction gratings is observed with easily made adjustments in the 3D printing design process. A square grating produced was found to be a (78±2)% efficient beam splitter. The blazed grating produced demonstrated an efficiency of (38±1)% in the first order diffraction maxima. These were taken using radiation at 0.28 THz using the two-color wave photomixing system.

I. INTRODUCTION/THEORY

Recent advances in 3D printing technology have seen large rises in available applications. With ever increasing resolution and affordability (20 µm for low cost) an opportunity is presented to produce good quality and inexpensive terahertz optical devices.

For terahertz radiation with large beam diameters (~20 mm) and short focal lengths, aspherical lenses are required to produce high spatial resolution [1]. Three such lenses are the planar-hyperbolic lens, elliptical aspheric lens and the symmetric pass lens. Using Fermat’s Principle (assuming no spherical aberration) the focal point of these lenses was given as 25 mm for High Density Polyethylene (HDPE), with index of refraction of 1.52 for the 0.3-1THz frequency range [1].

Scalar diffraction theory indicates that geometric considerations of diffraction gratings can lead to production of devices with desirable beam output [2]. For this paper diffraction gratings were generated via the convolution of a comb and rectangular function with an associated phase depth (pitch). By placing restrictions on the geometry of the gratings the output can be controlled. For example, for a square wave of pitch, d, and period, λ, if using the relation

\[(n-1)d = \lambda \tag{1}\]

the output should be restricted to even-order maxima with precise beam intensities given in [2]. A blazed grating can be approximated by a series of square gratings generated via a more complicated comb and rectangular convolution function. These gratings show higher maxima orders observed with the relative intensities in each maxima governed by how close or not the grating approximates the blazed grating and with phase considerations in the pitch depth.

The efficiency, η, of a square approximation to a blazed grating for N steps for the first-order diffraction maxima can be found from

\[\eta = \left[\sin\left(\frac{\pi}{N}\right)\right]^2. \tag{2}\]
**Aspherical Lenses:** The focal length of the three aspherical lenses was found to be (35±2) mm from an index of refraction of 1.64, determined using THz Time Domain Spectroscopy. Prematurely, this appears to contradict theory. However, the theory assumes that the cone angle and radial distance from the center of the lens have a linear relationship. This is true when using the thin lens approximation. This is not the case for the used aspherical lenses as shown in Fig. 3. The lenses used had a radial distance of 25 mm where a strong deviation from linear is observed. Accounting for the nonlinearity gives an expected focal length of 35.5 mm. Hence, the observed focal lengths agree with the theory once the nonlinearity is accounted for. The short focal length observed supports high spatial resolution imaging using these lenses should be achievable.

![Fig. 3. Relationship between cone angle and radial distance. Lenses used are shown as the darker dashed line (Elliptical-aspherical in key) [1].](image)

**Diffraction Gratings:** For the diffraction gratings produced the maxima position and relative intensities (as a percentage) are shown in Fig. 4. The square and blazed surfaces produced were both designed to give a diffraction angle of 45 degrees at 0.4 THz.

<table>
<thead>
<tr>
<th>m = 0 Order</th>
<th>m = ±1 Order</th>
<th>m = -1 Order</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Square Wave (Position)</strong></td>
<td>(0±0.5) Degrees</td>
<td>(+42.0±0.5) Degrees</td>
</tr>
<tr>
<td><strong>Square Wave (Intensity)</strong></td>
<td>(11±1)%</td>
<td>(39±1)%</td>
</tr>
<tr>
<td><strong>Blazed (Position)</strong></td>
<td>(+1.0±0.5) Degrees</td>
<td>(+44.0±0.5) Degrees</td>
</tr>
<tr>
<td><strong>Blazed (Intensity)</strong></td>
<td>(38±1)%</td>
<td>(38±1)%</td>
</tr>
</tbody>
</table>

![Fig. 4. Position and relative output maxima intensities for square wave grating.](image)

The square wave grating is seen as a first order approximation to that of the blazed grating. It is an equally good approximation in both directions, hence even distributions of light should be observed for corresponding maxima. This is observed experimentally and thus agrees with theory. Despite this, the theory predicts that 40.5% of the radiation should fall in the m = ±1 diffraction order. The theory also predicts that for the square wave grating, there should be a suppression of even orders, as the pitch is such to induce a π phase change. This is not observed with (11±1)% falling in the m = 0 order. However, this can be accounted for in experimental procedure, as the gratings were produced for optimal efficiency at 0.4 THz. The experiments were performed at 0.28 THz. This discrepancy is not only evidenced in the small m = 0 output but also the deviation away from the diffraction angles of 45 degrees to between 42-43 degrees. Despite this, a good correlation between theory and the experiment is observed, and the grating can be considered as a (78±2)% efficient beam splitter. Reproduction of these gratings for this wavelength and performing the experiment at 0.4 THz is a goal for future research.

For the blazed surface the theory predicts that all the radiation should fall into the m = 1 order. This was clearly not observed and results from two main causes. Firstly, the theory assumes an infinitesimally thin grating. However, having a bulk of the material results in an emitted wavefront slightly shorter than the period of the grating. This can be used to quantify the efficiency of the grating, as the square of this ratio is related to the ratio of the period over the wavelength. Theoretical data obtained from Eqn. (2) was used to calculate the expected efficiency of the blazed grating. This is shown in Fig. 5. The ratio of the period and wavelength for the grating used is found to be 1.9. From Figure 5 this gives an efficiency of n = 37% for this wavefront approach. This is consistent with experiment and confirms the experimental data, which shows (38±1)% efficiency into the first order.

The second main source of error is due to limitations in the manufacturing process. The blazed surface is assumed to be perfectly smooth which is not the case as the 3D printer builds the design in 100 μm steps. In addition, the base is assumed to be infinitely thin which is not achievable (in any fabrication process). This gives credence to design limitations but also suggests areas for future improvement by designing thinner gratings thinner, made with higher precision printers.

![Fig. 5. Blazed grating true efficiency as determined by Eqn. (2).](image)

In conclusion, all the lenses and gratings were produced at a low cost within a few hours of digital drawing completion. This demonstrates a simple and effective way of producing quality terahertz devices, and reveals a large potential for the production of further, more complicated devices.

**REFERENCES**