Mid-Infrared transmission gratings in chalcogenide glass manufactured using ultrafast laser inscription

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ABSTRACT

Ultrafast laser inscription is a versatile manufacturing technique which can be used to modify the refractive index of various glasses on a microscopic scale. This enables the production of a number of photonic devices such as waveguides, beam-splitters, photonic lanterns, and diffraction gratings. In this paper, we report on the use of ultrafast laser inscription to fabricate volume phase transmission gratings in mid-infrared transmitting chalcogenide glass.

We describe the optimisation of the laser inscription process parameters enhancing grating performances via the combination of spectrally resolved grating transmission measurements and theoretical analysis models. The first order diffraction efficiency of the gratings was measured at mid-infrared wavelengths (3-5 μm), and found to exceed 60% at the Littrow blaze wavelength, compared to a substrate external transmittance of 67%. This impressive result implies the diffraction efficiency should exceed 90% for a grating substrate treated with an anti-reflection coating. There is excellent agreement between the modelled grating efficiency and the measured data, and from a least squares fit to the measured data the refractive index modulation achieved during the inscription process is inferred. These encouraging initial results demonstrate that ultrafast laser inscription of chalcogenide glass may provide a potential new and alternative technology for the manufacture of astronomical diffraction gratings for use at near-infrared and mid-infrared wavelengths.

Keywords: Chalcogenide Glass, Diffraction Grating, Ultrafast Laser Inscription, Mid-infrared

1. INTRODUCTION

Instrumentation engineers are constantly looking for new methods, technologies, materials and manufacturing techniques that will improve the performance of future spectrographs. This is particularly relevant when designing new instrumentation for use at mid-infrared wavelengths where the available range of materials and manufacturing techniques is somewhat less than for optical or near-infrared instrumentation. To be useful, any new technologies that are developed should also be capable of providing significant performance benefits in terms of higher optical efficiency, lower cost, robustness, and smaller volume. An important new technology that provides all of these benefits is the use of Ultrafast Laser Inscription (ULI) to process dielectric materials, which has been demonstrated in the fabrication of a variety of photonic components such as waveguides [1], beam-combiners [2], multi-mode to single-mode fan out devices [3][4], and diffraction gratings [5].

The ultrafast laser inscription process has been described in detail elsewhere [1], and utilizes a high peak power laser beam operating with ultrashort pulses, which is focussed into the material to be processed. This causes a permanent refractive index change, which can be positive or negative depending on the laser operating parameters. Translation of

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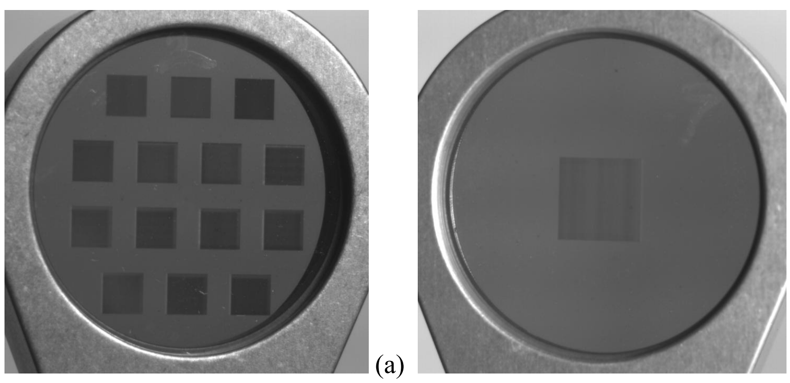
the glass position relative to the beam enables complex three-dimensional photonic structures to be written in the material.

This paper describes the latest results from a collaborative project to develop mid-infrared photonic technology platforms, including ULI diffraction gratings. The aim of this work is to produce efficient grating structures that can be used in a variety of future instrumentation projects, such as Earth observation instruments, laser cavities, and mid-infrared spectroscopic instruments for large telescopes.

This paper has been divided into a number of sections describing various aspects of the mid-infrared grating development work. Section 2 describes the technique used to manufacture the grating structures, Section 3 presents the results of theoretical modelling of grating efficiency, Section 4 describes how the efficiency of the gratings was measured, and Section 5 presents the results. The final section presents the summary and conclusion.

2. GRATING MANUFACTURE

A number of prototype gratings were manufactured in chalcogenide glass using the ULI process described in previous publications [6][7]. Chalcogenide glass was chosen due to its high transparency over the wavelength range of interest, covering 3 – 10 μm. Following the previously published procedure [6][7], the initial prototype gratings were written in groups of 14, as shown in Figure 1(a), with each grating inscribed at slightly different laser pulse energy. Each of the 14 gratings was tested to measure its efficiency in order to find the grating with the best performance, and hence determine the optimum laser pulse energy. Once the optimum laser pulse energy had been identified a series of larger mid-infrared gratings, as shown in Figure 1(b), were manufactured. To achieve increased efficiency in the mid-infrared, the volume depth of the gratings was increased using a larger number of layers than the initial smaller prototypes. The larger mid-infrared gratings were positioned at the centre of the glass substrates to aid alignment during optical testing.



(a) (b)

Figure 1. Picture of laser-inscribed gratings in chalcogenide glass, taken using near-infrared light.

3. THEORETICAL EFFICIENCY MODELLING

Theoretical predictions of grating spectral efficiency were calculated using the commercial software package GSolver. The gratings were modelled with a substrate refractive index as per the glass manufacturer's data sheet, line spacing (period) of 3 μm, and illumination with unpolarised light. The assumed properties of the inscribed region were based on our previous measurements [7], and from calculations based on preliminary efficiency measurements.

Three grating modelling parameters were adjusted to obtain the best fit between the theoretical predictions and the measured efficiency data: the refractive index of the inscribed region, the width of the modified region, and the overall depth of the modified region.

The theoretically-predicted first order Littrow efficiency curve for an example laser-inscribed diffraction grating in chalcogenide glass, modelled with a volume depth of 130 μm and assuming unpolarised light, is shown in Figure 2. The theoretical maximum diffraction efficiency of 66% at 3.1 µm is impressive when compared with the transmittance of the substrate which is limited to 67% by Fresnel reflection losses at the air-glass interfaces. The theoretical efficiency model shown in Figure 2 includes the losses due to the air-glass surfaces. At the wavelength of the first order efficiency peak, the remaining light diffracted into the others orders is approximately 1%, hence losses into higher orders are negligible. It is the line width geometry created by the ultrafast laser inscription technique that enables such high first order diffraction efficiency to be achieved, whilst minimizing losses into other diffraction orders.

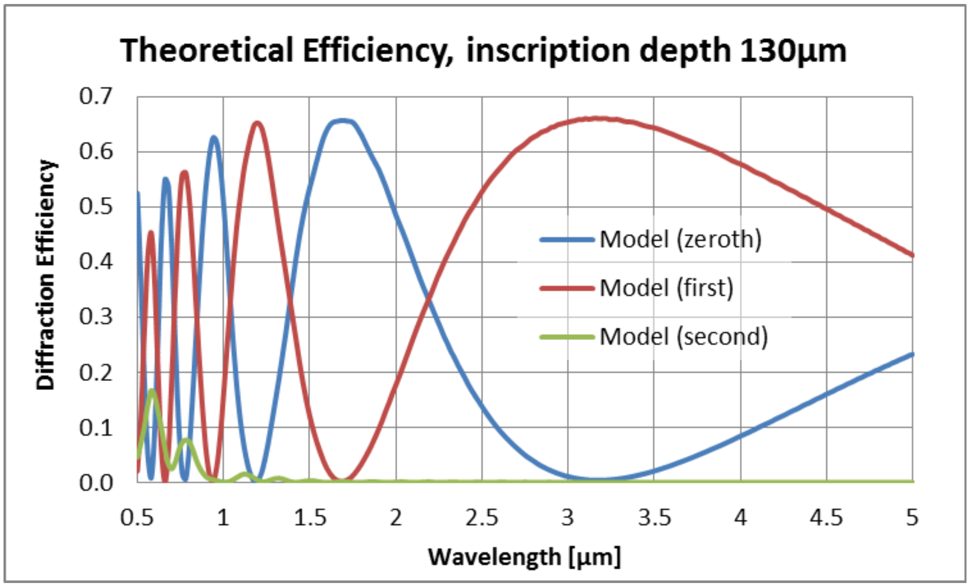


Figure 2. Predicted theoretical Littrow efficiency curve for a laser-inscribed grating in chalcogenide glass.

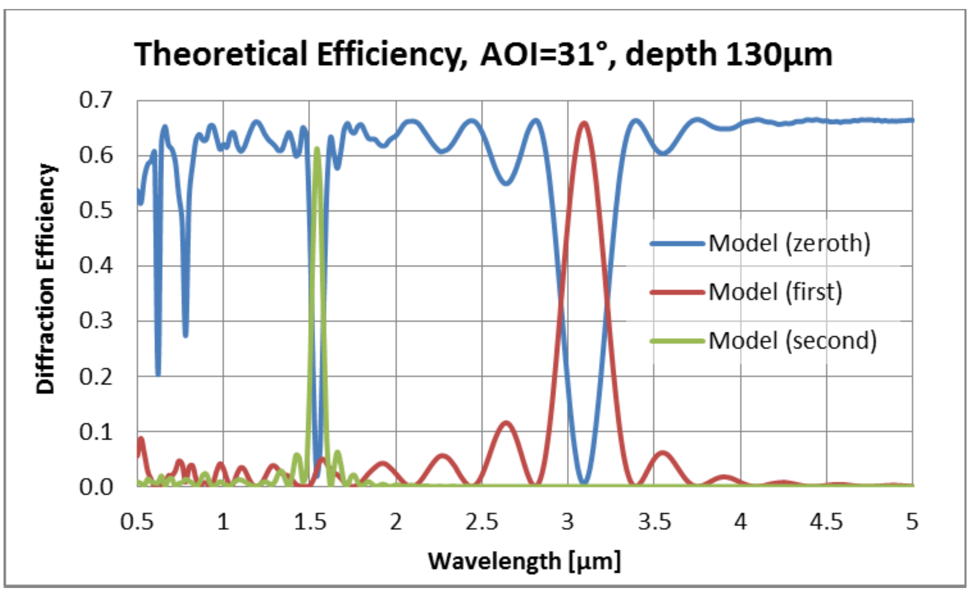


Figure 3. Predicted theoretical efficiency curve for a laser-inscribed grating in chalcogenide glass, operating at fixed angle of incidence of 31 degrees.

The peak Littrow efficiency occurs at an angle of incidence (AOI) of 31 degrees, and the theoretical efficiency of the grating when operated at this fixed angle is shown in Figure 3. There is prominent first order transmission peak at 3.1 µm with a corresponding drop in the zeroth order efficiency at the same wavelength. There is also a prominent zeroth order dip at 1.55 µm which coincides with a strong second order diffraction peak. There is also evidence of weak fourth (0.78 µm) and fifth (0.62 µm) order dips in the zeroth order efficiency curve, but no third order dip (expected at 1.03 µm). During the theoretical modelling process it was discovered that the presence or absence of higher diffraction orders is related to the line width of the modified region.

4. TEST PROCEDURE

4.1 Efficiency tests with monochromatic light

The diffraction efficiency of the prototype chalcogenide diffraction gratings was initially measured at the UK Astronomy Technology Centre using the test facility described in an earlier paper [7]. In summary, the test setup consisted of an intensity stabilized white light source, a commercial grating monochromator illuminating a collimation lens, the grating under test, and a near-infrared camera to measure the intensity of the diffracted beams. The grating was tested over a range of wavelengths, typically 1.0 – 2.5 µm. During testing, the position and angle of incidence of the grating was adjusted using commercial positioning stages, to maintain alignment, and optimise the diffraction efficiency.

4.2 Efficiency tests with a Fourier transform spectrograph

To extend the wavelength range of efficiency measurements to mid-infrared wavelengths, the prototype chalcogenide gratings were measured using a Fourier Transform Spectrograph (FTS). The instrument used for the efficiency measurements was a Bruker Vertex 80V, which is part of the extensive range of instrumentation operated by STFC's high resolution spectroscopy facility at the Rutherford Appleton Laboratory.

The grating under test was placed in to the sample compartment of the FTS and the absorption spectrum of the grating was measured. The grating was held in the sample compartment using a specially designed mount, as shown in Figure 4, which enabled the angle of incidence of the grating to be varied. The FTS only measures the undeviated zeroth order beam, shown in orange in Figure 4; the other diffraction orders, shown in red in Figure 4, are not measured directly, but a low zeroth order efficiency is evidence of a high first order (or higher order) efficiency, as shown theoretically in Figure 2 and 3.

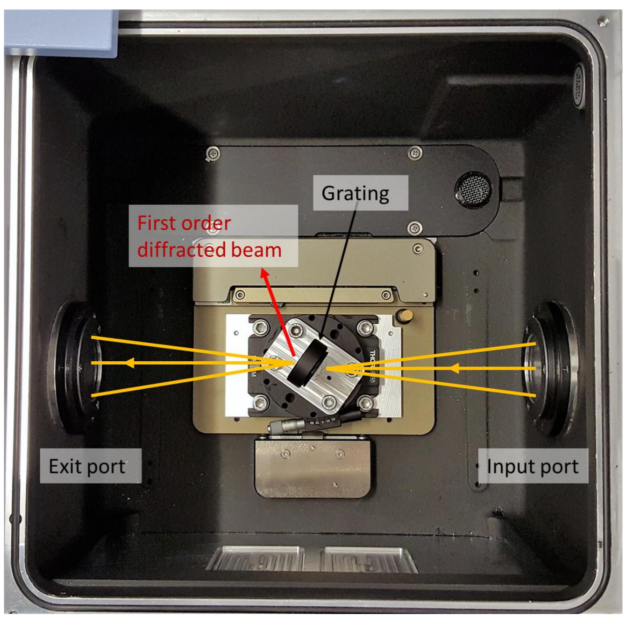


Figure 4. Picture of a grating mounted within the sample chamber of the FTS.

The FTS was also used in a collimated beam configuration, with an additional accessory fitted to the sample compartment. A picture of the collimated beam optics and grating is shown in Figure 5. The beam path is illustrated in orange and red for the uncollimated and collimated beams, respectively. As before, only the zeroth order beam is measured.

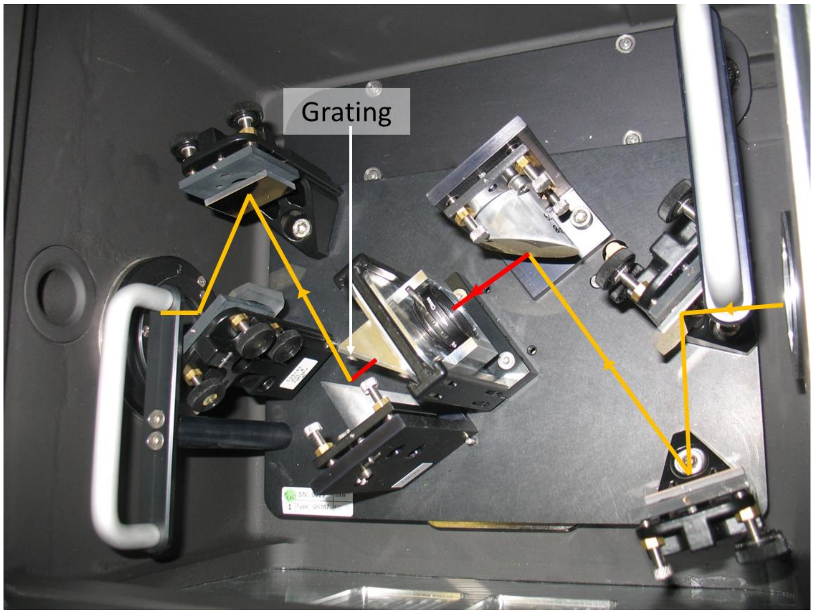


Figure 5. Picture of a grating mounted in the collimated beam accessory for the FTS.

5. EFFICIENCY RESULTS

5.1 Monochromator measurements

The measured zeroth and first order diffraction efficiency of a prototype laser-inscribed grating in chalcogenide glass is shown in Figure 6. This grating was manufactured with 22 laser-inscribed layers, and has a similar appearance to the grating shown in Figure 1(b).

The first order Littrow efficiency peaks at 63% at approximately 2.4 µm, whilst the first order efficiency drops to below 5%. The best fit theoretical model of the grating behavior is also shown in Figure 6 for comparison. The measured data stops at 2.5µm due to the upper wavelength limit of the test equipment, described in section 4.1, but extrapolation of the theoretical curve shows that first order efficiency is maintained well into the mid-infrared (3 – 5 µm) wavelength range.

The measured data has an experimental uncertainty of ±2%.

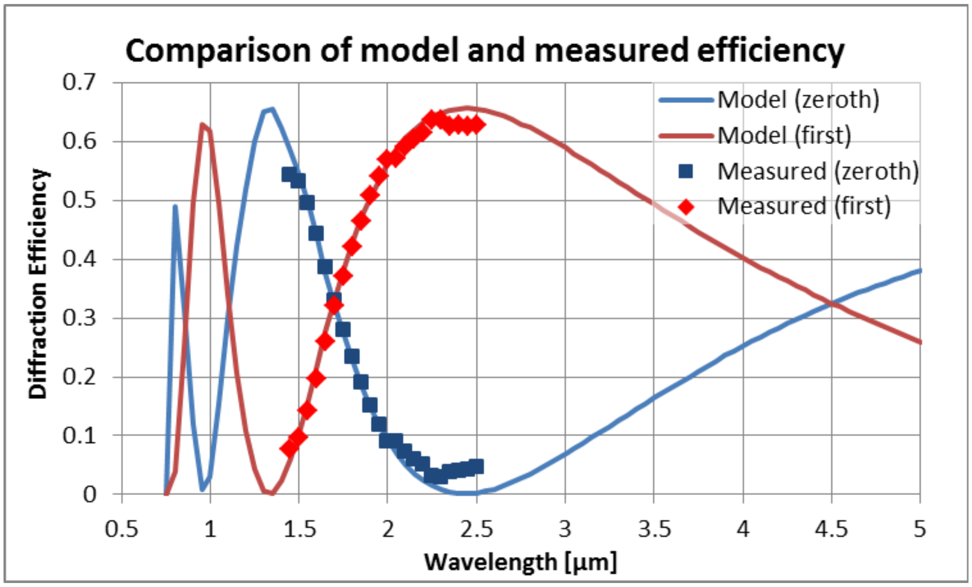


Figure 6. Comparison of the measured zeroth and first order efficiency of a laser-inscribed chalcogenide grating (points), and the theoretical efficiency model (lines).

5.2 Fourier transform spectrometer measurements

The zeroth order transmission spectrum of a prototype mid-infrared grating, measured at angles of incidence 25, 30, 35, 40, 45, and 50 degrees, is shown in Figure 7. This grating, shown in Figure 1(b), was manufactured with 30 laser-inscribed layers. There are clear dips in the zeroth order transmission approximately centred at wavelengths 2.5, 3.0, 3.4, 3.8, 4.2, and 4.6 µm, which are caused by first order diffraction at the angles of incidence listed. The dips are, however, not as deep as predicted in Figure 3, and the full width at half-maximum (FWHM) of the measured features are much broader than shown in Figure 3. The broadening of the absorption features is caused by the angular diversity of the convergent incident beam (input angles spanning approximately ±4 degrees) in contrast to the collimated incidence used in the model. Figure 4 illustrates these experimental conditions.

The theoretical grating model was adjusted to calculate the average efficiency taking into account the convergent illumination condition. An example theoretical model output, for angles of incidence 31–39 degrees, is shown in Figure 8, alongside the measured data at 35 degrees centre AOI. The averaged theoretical model provides a better fit to the measured data, showing a first order efficiency dip at 3.5 µm, similar FWHM, and also a good match to the second order efficiency dip at 1.75 µm. It is difficult to estimate the first order efficiency from these convergent measurements, but Figure 8 does indicate the grating is not performing as efficiently as expected from the theoretical model, with the zeroth order efficiency falling from 60% to 45%, compared to a fall to 40% for the theoretical data.

Despite the convergent beam affecting the interpretation of the results, the prototype laser-inscribed mid-infrared grating clearly exhibits diffraction performance over a broad range of wavelengths from 2 – 5 µm, as predicted in Figure 2.

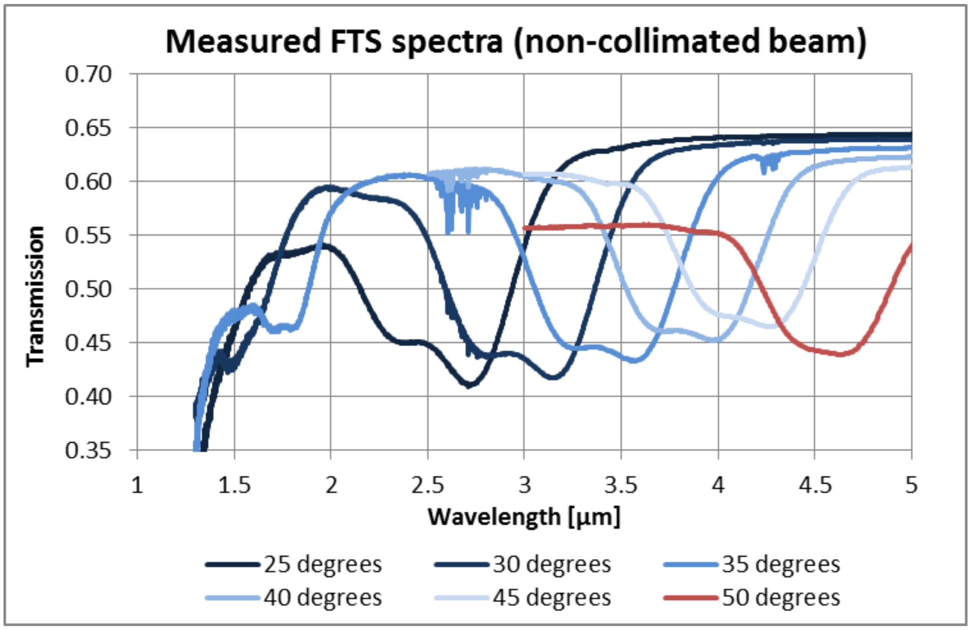


Figure 7. FTS zeroth order transmission spectra of a mid-infrared grating, measured at various AOI as listed in the legend.

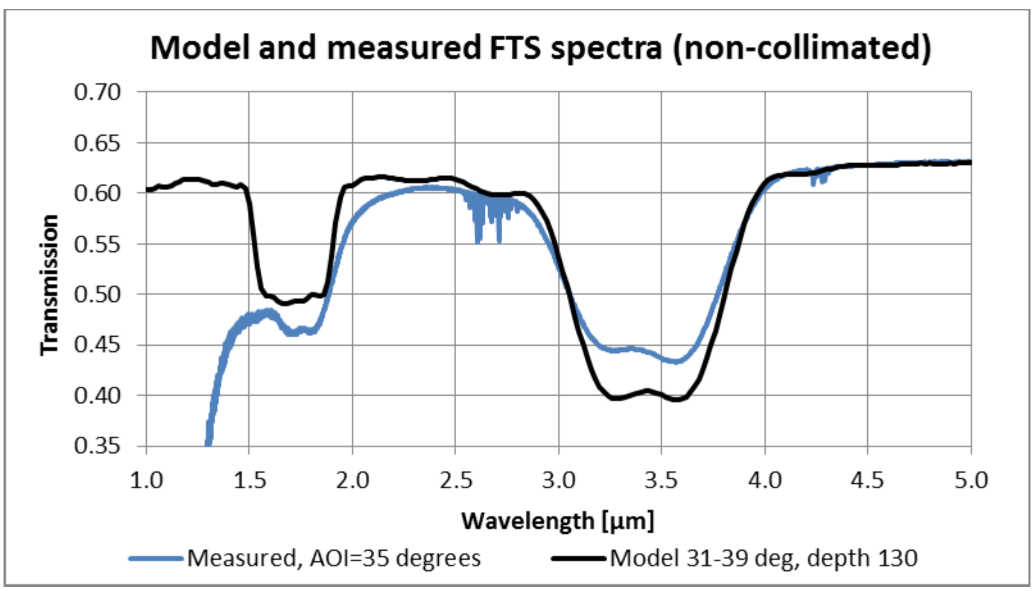


Figure 8. Comparison of the measured FTS spectrum (zeroth order efficiency) of a mid-infrared laser-inscribed chalcogenide grating (blue line), and the theoretical efficiency model (black line).

A further set of data was collected at an AOI of 35 degrees using the collimated beam accessory of the FTS, as shown in Figure 5. This data is shown in Figure 9, in comparison with the theoretical best fit model. The theoretical model now shows good agreement with the measured data in the region where the first order diffraction occurs, causing the dip in zeroth order efficiency at 3.5 µm. The zeroth order transmission falls from 57% to 25%, a decrease of 32%, which implies the first order efficiency is therefore approximately 32% assuming no other diffraction orders propagate at this angle and wavelength.

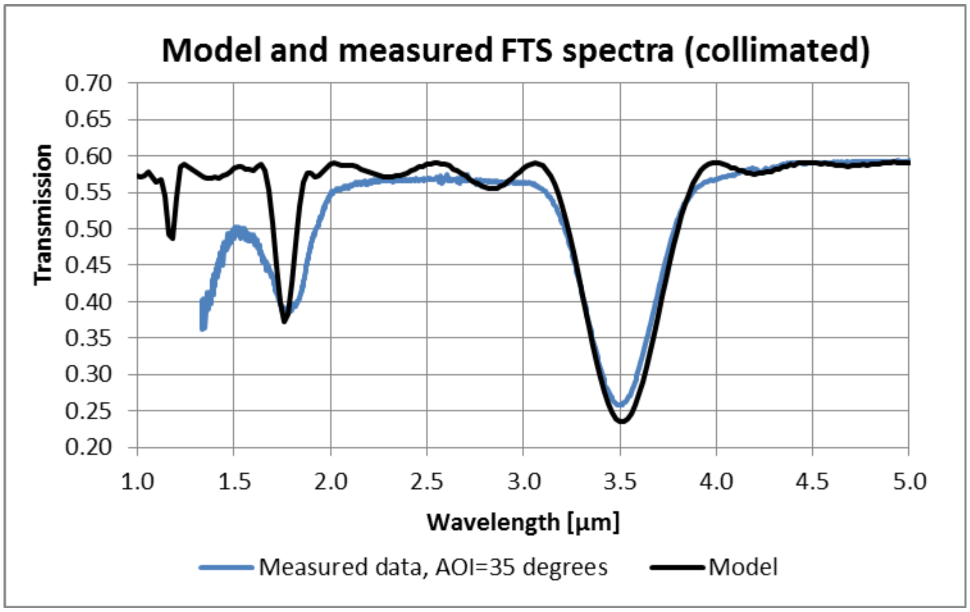


Figure 9. Comparison of the measured FTS spectrum (zeroth order efficiency) of a mid-infrared laser-inscribed chalcogenide grating (blue), and the theoretical efficiency model (black).

It should be noted that these efficiency data are for prototype gratings manufactured in chalcogenide glass substrates that have not yet been treated with an anti-reflection coating. It is expected that an anti-reflection coating would increase the substrate transmittance from 67% to near 99%, as described in [8]. The effect of an anti-reflection coating on the first order efficiency data shown in Figure 6 would be to increase the efficiency to ~93%, whilst the inferred first order efficiency of the grating data shown in Figure 9 would become ~47%.

6. SUMMARY & CONCLUSION

This paper presents the theoretical modelling and initial efficiency test results for a number of prototype mid-infrared diffraction gratings manufactured in commercially available chalcogenide glass. Theoretical efficiency predictions showed promising results, with high first order efficiency, and zeroth order efficiency reducing to near zero. Initial near-infrared efficiency tests on small prototype gratings, shown in Figure 1(a), were used to optimise the parameters of the ultrafast laser inscription manufacturing process. A number of larger mid-infrared optimised gratings were then manufactured and efficiency tests were performed to demonstrate their mid-infrared performance. The best performing grating achieved a first order efficiency of 63% at 2.4 µm (Figure 6), whilst the mid-infrared efficiency of a different grating at 3.5 µm was inferred to be 32% (Figure 9). These promising initial results are expected to be improved by the application of anti-reflection coatings to the chalcogenide glass substrates.

These preliminary results are the first demonstration of the mid-infrared performance of laser-inscribed gratings in chalcogenide glass operating at wavelengths above 3.5 µm. It is expected that future mid-infrared spectroscopic instrumentation requiring efficient gratings will benefit from this new technology.

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