ANALYSIS AND DESIGN OF BLAZED GRATINGS WITH EXTENDED SPECTRAL RANGE IN THE THz FOR SPACE INSTRUMENTATION

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INTRODUCTION

The exploration of radiation in the terahertz range is a subject of increasing interest within the scientific community. The scarcity of instrumentation has resulted in a paucity of knowledge regarding the region between 30 and 1,000 µm (10-0,3 THz). However, recent technological advances have rendered it feasible to propose viable new space missions to study this range. The fabrication of optical components optimized for this range poses a significant technological challenge due to the size of these components. The advent of innovative fabrication methodologies, exemplified by femtosecond laser micro-machining, has enabled the creation of freeform geometries with very precise surface finishes. The design, fabrication and characterization of a diffraction grating in the terahertz range, working in the 70 to 114 micron range (4,3 – 2,6 THz), has previously been presented, with an experimental efficiency of more than 85% over the whole range. In this contribution, we present the theoretical proposal of a grating with a freeform profile that allows to obtain efficiencies higher than 65% in an extremely long wavelength range, from 40 to 140 microns (7,5 -2,1 THz), in a single diffraction order. This grating will be manufactured using femtosecond laser techniques. To this end, the effect of different design parameters on the theoretical efficiency has been studied using software based on the RCWA (Rigorous Coupled-Wave Analysis) method. An additional study using FEM (Finite Element Method) software has been carried out to validate the results obtained by RCWA. The use of this type of wide-range diffractive components will optimize the instruments volume and therefore reduce costs.

PREVIOUS CONTRIBUTIONS

Spectral Range	[70-114] µm
Diffraction Order	1
Polarization	TM
Material	Aluminum
Total Diffraction Angle (TDA)	30-40°
Diffraction Efficiency (DE)	>85%
Angle of incidence (ϑ_{inc})	57°

Table 1. Diffraction grating parameters.

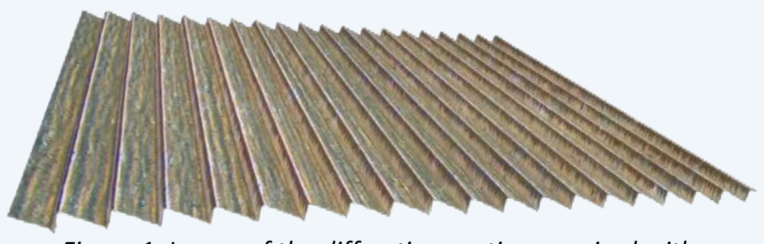

Figure 1. Image of the diffraction grating acquired with confocal microscopy.

- A blazed diffraction grating optimized for the 70 to 114 micron range (4,3 – 2,6 THz), but capable of operating in the 60 to 130 micron range (5 – 2,3 THz), with efficiencies above 85 % in order 1(TM polarization), was designed, fabricated and characterized. The grating parameters are given in Table 1.
- Figure 1 shows a confocal microscopy image of the grating fabricated with a 5-axis femtosecond laser system. The result of the fabrication satisfies the design requirements. Figure 2 compares the fabricated profile with the designed one.
- The experimental characterization was carried out using a Quantum Cascade Laser (QCL) capable of emitting at 5 wavelengths in the range of interest. Figure 3 shows the theoretical efficiency curve versus the measured diffraction efficiency. The results are very close to those predicted by theoretical simulations.
- Based on this successful design, our goal is to extend the working range of the grating from 40 to 140 microns with diffraction efficiencies of over 65%.

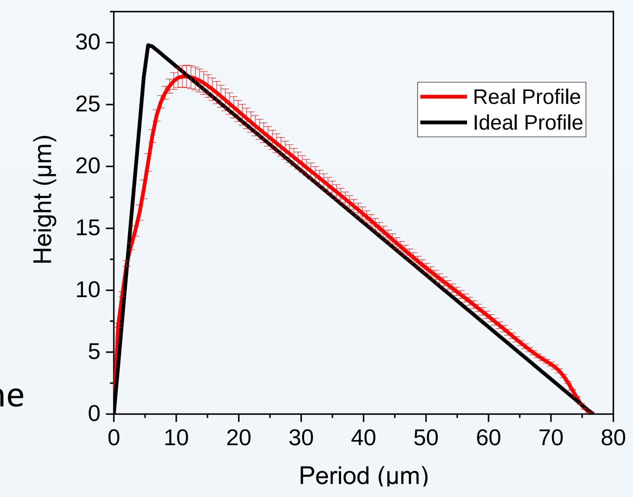

Figure 2. Sawtooth profile: Ideal vs Real.

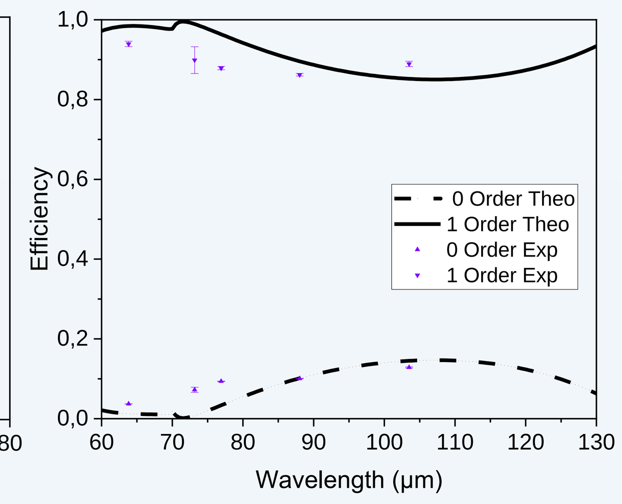

Figure 3. Diffraction efficiency obtained experimentally vs theoretical efficiency curve.

FREEFORM GRATING DESIGN

Blazé gratings are able to achieve very high efficiencies in a single diffraction order when the wavelength range is limited to the existence of orders 1 and 0. As the wavelength range increases, the energy is distributed over the different orders and complex geometries must be used to concentrate all the diffracted energy in a single order. The following figures show how the different parameters affect the efficiency of the grating at order 1 in the range of 30 to 140 microns. The simulations were carried out using software based on the RCWA method. In all simulations, the period (76 µm), the material (Aluminum), the angle of incidence (57°), the polarization (TM), the number of layers (100) and the number of orders used for the simulation (20) have been kept constant. The graphs show a color map with the variation of the efficiency vs. wavelength and as function of the parameters studied. The black line demarcates the region where efficiency represents more than 65%.

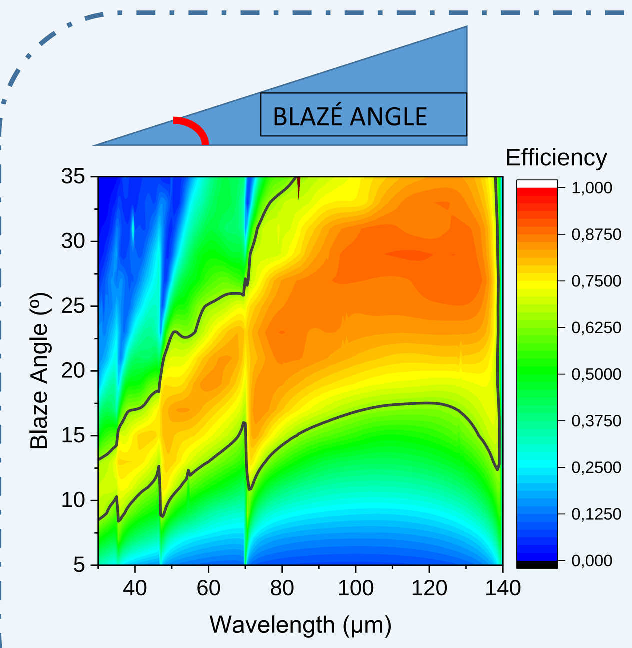

Figure 4. Diffraction efficiency vs. wavelength as function of Blazé angle

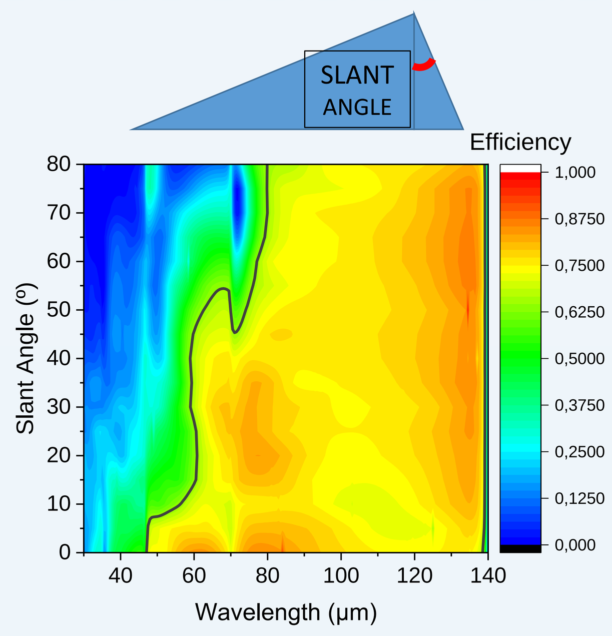

Figure 5. Diffraction efficiency vs. wavelength as function of slant angle.

The influence of the Blazé angle (Figure 4) and the Slant angle (Figure 5) on the efficiency has been analyzed :

- An increase in Blazé angle is associated with an improvement in the efficiency for long wavelengths and a reduction in it for short wavelengths.
- An increase in slant angle is accompanied by a reduction in efficiency. Laser manufacturing will always introduce a slant angle.

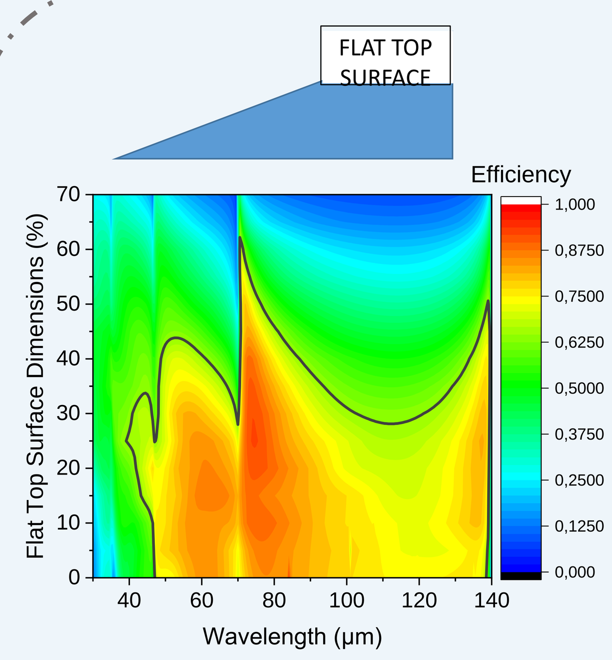

Figure 6. Diffraction efficiency vs. wavelength when the apex of the profile is flattened.

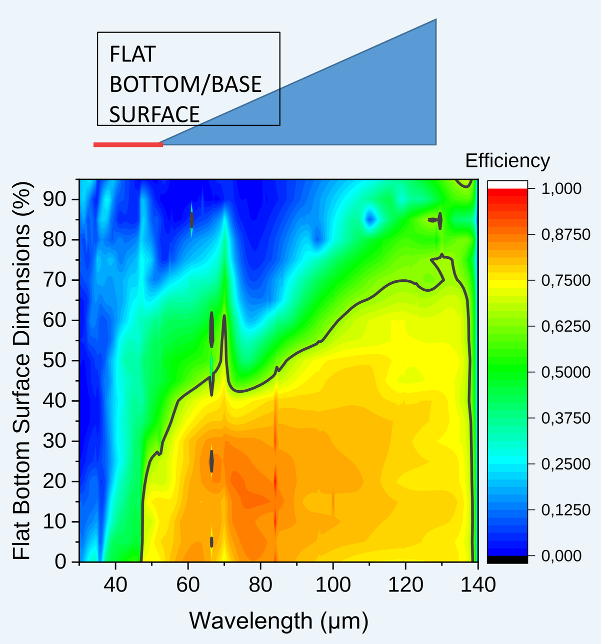

Figure 7. Diffraction efficiency vs. wavelength when the profile base is flattened.

The following figures show the effect on the efficiency of incorporating a flat surface at the apex of the profile (Figure 6), or at the base of the profile (Figure 7):

- Incorporating a flat surface at the apex of the profile can improve efficiency at short wavelengths, although when the flat surface exceeds 35% of the total base, the efficiency decreases at mid-wavelengths.
- The manufacturing method produces flat surfaces at the base of the profile. The greater the proportion of the period occupied by this flat surface, the lower the efficiency value, especially at short wavelengths.

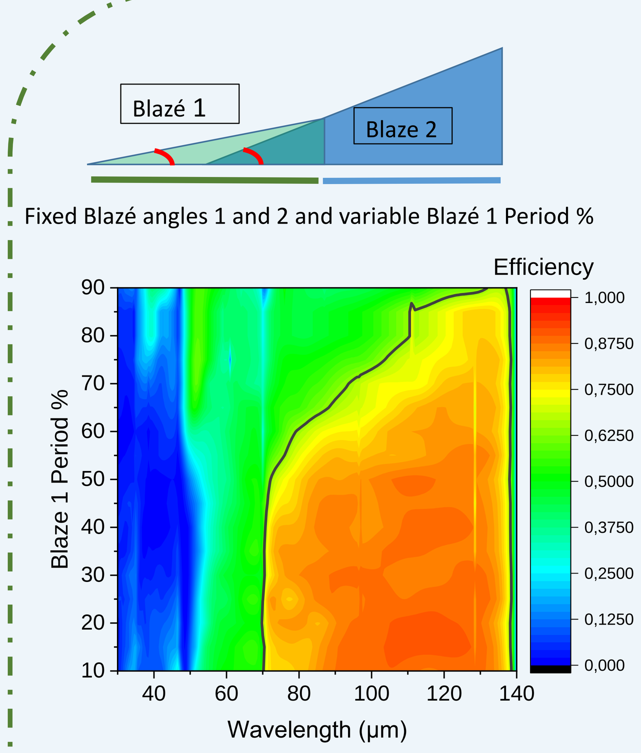

Figure 8. Diffraction efficiency vs wavelength when introducing a double slope in the profile. The Blazé angle of each slope remains constant but the percentage of period corresponding to Blazé 1 varies.

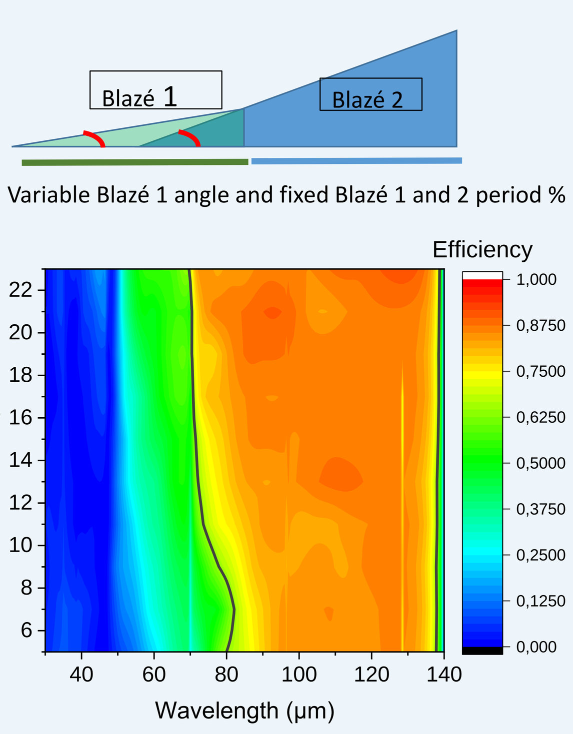

Figure 9. Diffraction efficiency vs wavelength when introducing a double slope in the profile. The proportion of period occupied by each slope is retained at 50% but the first Blazé angle is varied while keeping the second constant.

The following figures show a double Blazé profile. In figure 8 the Blazé angles remain constant, the first Blazé is 10°, the second is 27°, and the proportion of period corresponding to each angle of Blazé is varied. In figure 9 the ratio of periods occupied by each Blazé angle is kept constant (50%), while the Blazé angle 2 is constant 27°, and the angle of Blazé 1 varies from 5° to 23°.

- When the proportion of the period corresponding to the smallest Blazé angle exceeds 50%, the efficiency drops especially at short and medium wavelengths.
- When the ratio of the period covered by each Blazé angle remains constant, an increase in the angle of the first Blazé improves the efficiency of the grating.

The diffractive behavior of the grating when several different parameters are combined differs from that expected when each element is considered separately. The grating has therefore been optimized taking into account all possible configurations using a software based on the RCWA method.

To achieve a grating operating over the whole range of interest with efficiencies above 65%, after the optimization process, the profiles shown in Figure 10 has been proposed. The description of which are summarized in Table 2.

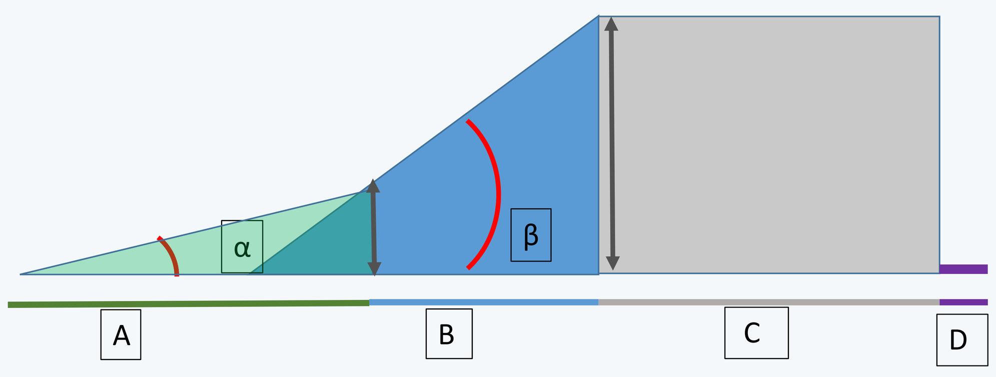

Figure 10. Freeform blazed grating.

Parameter	Dimension
Region A	27,66 µm
Region B	18,24 µm
Region C	26,45 µm
Region D	3,65 µm
Blazé angle α	10°
Blazé angle β	33,5°

Table 2. Freeform diffraction grating parameters.

The profile consists of:

- A flat part at the base of the profile occupying 5% of the total period (Period D).
- A double Blazed profile optimized to have good efficiencies at short wavelengths (Blazé angle α = 10°) without losing much efficiency at long wavelengths (Blazé angle β= 33,5 °).
- A flat part at the apex of the profile that improves efficiency at short wavelengths (Period C corresponding to 35% of the total period).

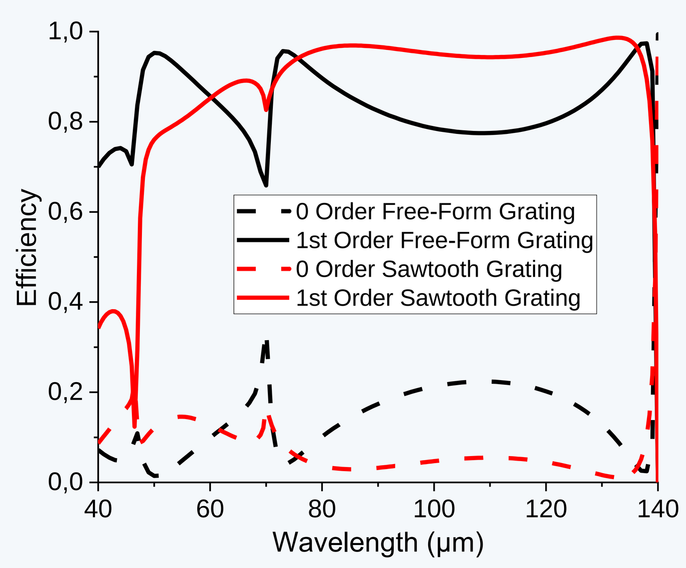

Figure 11. Theoretical diffraction efficiency of a Blazé grating shown in Figure 2 (red line) versus the diffraction efficiency of the proposed freeform grating shown in Figure 10 (black line).

Range (µm)	Freeform shaped grating Average Efficiency	Sawtooth shaped grating Average Efficiency
40-140	0,83±0,07	0,87±0,17
40-70	0,82±0,09	0,70±0,22

Table 3. Efficiency for Freeform and saw-tooth grating in different ranges

Figure 11 illustrates the theoretical efficiency of diffraction gratings with sawtooth and freeform profiles. Table 3 shows the comparative of the diffraction efficiency as function of different spectral range between a freeform shaped grating and a sawtooth shaped grating.

- The freeform profile exhibits greater uniformity in efficiency across the entire wavelength range, as evidenced by the lower standard deviation, though its efficiency is 5% lower than that of the sawtooth grating.
- In the short wavelength region the efficiency improvement is 12% with a much lower standard deviation.

CONCLUSIONS

The development of new manufacturing techniques enables the fabrication of optical components with complex structures that improve their performance. The use of diffraction gratings working over a wide range of wavelengths makes it possible to reduce the number of elements needed to analyze a wide bandwidth of radiation, thus reducing mass, volume and costs. To achieve high diffraction efficiencies over a wide spectral range it is necessary to use complex freeform profiles capable of concentrating all the radiation in a single diffraction order. The incorporation of a double Blazé profile, a flat surface both at the apex and at the base of the profile, improves the efficiency at short wavelengths, where more than one order of diffraction coexists, without degrading the long wavelengths efficiency. We present a proposed freeform diffraction grating that improves efficiency by 12% at short wavelengths, and meets the requirements of achieving efficiencies above 65% over the entire bandwidth range.

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