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Femtosecond laser direct writing of a Fresnel zone plate in glasses for mid-infrared imaging applications

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ABSTRACT

An important challenge in infrared imaging today consists in addressing the SWaP problem (Size, Weight and Power), for example by simplifying as much as possible the optical system before the sensor. The work presented in this paper takes advantage of recent techniques in femtosecond laser direct writing to imprint optical systems.

This work aims at merging a lens array with a filter array by writing gradient index lenses with a femtosecond laser inside a dedicated glass substrate. A classical gradient index lens requires a huge refractive index variation, which cannot be reached today with femtosecond laser processing ($\Delta n_{max} \sim 0,05$). So, we decided to turn towards writing a gradient index Fresnel lens. A first-order Fresnel lens was designed with a $\Delta n_{max} < 5.10^{-2}$ discretised into 8 index levels to guarantee a diffraction efficiency of 85% on the overall spectral bandwidth of the filters.

We studied a chalcogenide glass because of his good properties in mid-IR optics. We compared the different laser responses of the material: threshold of permanent changes, quantitative phase and index variation.

Finally, we showed that reaching a phase variation of π radians with femtosecond laser writing is possible even for a huge scanning speed (0,01 mm/s up to 25 mm/s). By overlapping the written lines, we were able to implement a maximum phase variation of 8 radians (with only one written layer), demonstrating the possibility to write quickly a GRIN Fresnel lens with a diameter of some millimeters.

Keywords: Optical design, Gradient Index, Laser writing

1. INTRODUCTION

The SWaP problem (Size, Weight and Power) is an important challenge today in infrared imaging. In order to simplify the optical system before the sensor and to keep high image quality, optical designers have to find new degrees of freedom in their designs. Several ways are thus explored like freeform optics [1], GRIN (gradient index) optics [2] and metasurfaces [3].

GRIN optics involve creating a spatial variation of the refractive index in the material. This index variation can correct some optical aberrations such as spherical aberration or chromatic aberrations [4] or encodes the optical power inside the lens (not just at surfaces).

One of the main limitations of GRIN optics is their manufacturing [5]. Most of the fabrication techniques can only create classic index variation (axial or radial) but freeform or even aspheric index profiles are very difficult to create. Some solutions exists in visible materials with thin film coating but it is much more complicated for infrared materials. This paper focuses on femtosecond laser direct writing, whose main advantage is to be very flexible.

By focusing an ultrafast laser in a substrate, this technique can change locally the density and, as a consequence, the refractive index of the material. It is already well known in visible and near infrared (IR) materials such as silica [6] but few studies concern materials used in mid-IR optics (chalcogenide) [7].

This paper presents how to simplify a multispectral camera by merging a lens array with a filter array, with gradient index lenses obtained by femtosecond laser writing inside a dedicated glass substrate.

2. A GRADIENT INDEX PLATE IN A MULTISPECTRAL CAMERA

2.1 Multispectral camera

ONERA has developed a multichannel multispectral camera whose concept is illustrated in *Figure 1*. It consists in an array of 2×2 lenses with a focal length of 7 mm and a F/4 F-number. Each channel has a field of view of 40°×30° and forms a 320×256 pixels image on each quarter of the detector. An array of 2x2 filters is placed after the lens array, so that each optical channel corresponds to a different spectral band with a width of about 200 nm.

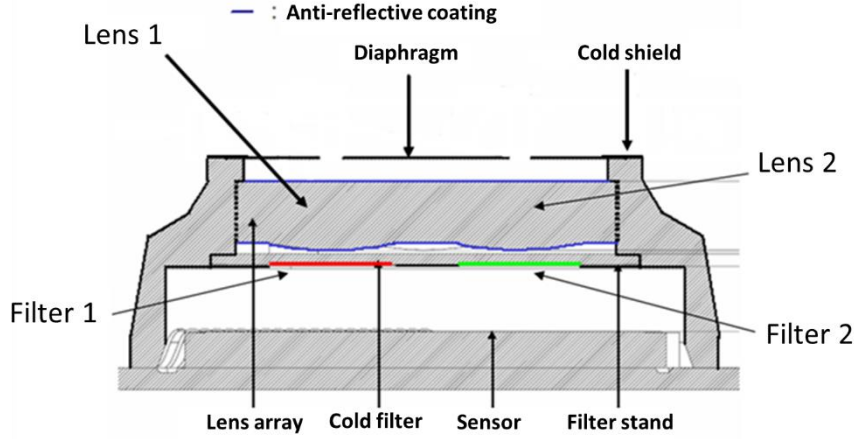


Figure 1. Cross-section of the ONERA multispectral camera. From top to bottom, the diaphragm, the lens array, the filter array and the sensor.

The optical system is composed of two objects, a lens array for imaging and a filter array to select a specific spectral band for each channel. These components are integrated in a cold shield of a Detector Dewar Cooler Assembly (DDCA) and are cooled at cryogenic temperature. These additional masses tend to increase the cool-down time of the DDCA. In order to address the SWaP problem for this camera, we want to remove one of the components. The filter array is an interference filter made by a multiple thin layers deposition on a substrate. It is difficult to deposit these films on a non-planar surface such as the lens array. So, the solution is to use a unique GRIN optic plate for the focusing and filter functions. In the rest of the paper, we will study only one channel of the multichannel camera.

A GRIN focusing plate needs a radial index variation to create an optical power instead of the spherical surfaces. A classical index profile used in this case is described in *Eq. 1*:

$$n(r) = n_0 + n_r r^2 \quad (1)$$

With n_0 the index on the optical axis, r the radial position and n_r the coefficient of index variation. This index distribution gives to the optical plate a vergence V of [8]:

$$V = -2n_r t = -\frac{\Delta n}{R^2} t \quad (2)$$

With t the thickness of the plate, Δn the index variation and R the radius of the lens. The issue with this index profile is to have a short focal length (ie a huge vergence). The vergence is proportional to the index variation (*Eq. 2*) so the camera studied needs an important index variation. For a 7 mm focal length in our case, this type of design needs a gradient index higher ($\Delta n = 0,11$ for a thickness of 1 mm) than what a femtosecond laser direct writing can create. *Eq. 3* gives the maximum index variation reachable today in mid-IR components with the femtosecond laser writing technique [9].

$$|\Delta n_{max}^{laser}| = 0,05 \quad (3)$$

2.2 GRIN Fresnel lenses

In order to reduce the index variation and preserve the small thickness of this component, the purpose is to code a Fresnel GRIN lens instead of a classical GRIN lens. This involves cutting a continuous surface into a series of discontinuous rings. The Fresnel versions of a spherical lens and GRIN lens are shown in *Figure 2*.

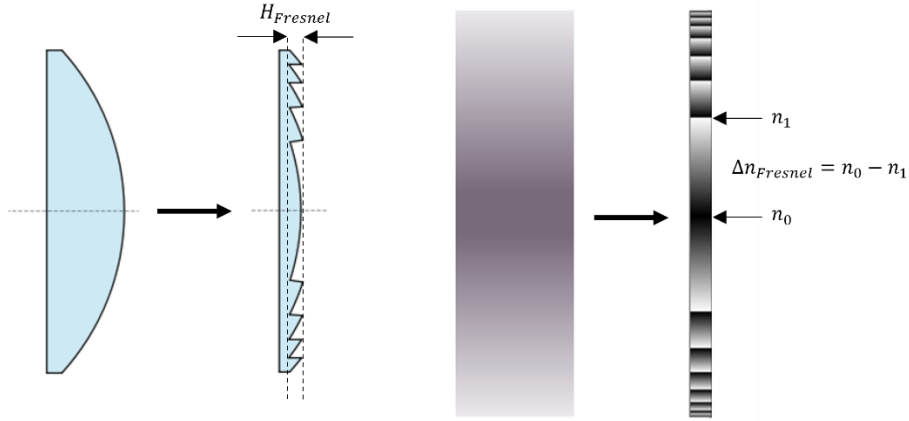


Figure 2. From a classical lens to a Fresnel lens and from a GRIN lens to a GRIN Fresnel lens.

Given that a GRIN index profile is equivalent to a surface sag of a conventional lens, the modeling of a Fresnel lens can be done in the Zemax software with a “User Define Surface” created for conventional Fresnel lenses. The surface sag used in the software is then converted into an index profile distribution. The surface sag ($z_{Fresnel}$) equation is described in Eq. 4 [10].

$$\left\{ \begin{array}{l} z_{Fresnel}(r) = \frac{cr^2}{1 + \sqrt{(1 - (1 + k)c^2r^2}}} \text{ mod } H_{Fresnel} \\ H_{Fresnel} = \frac{\lambda_0}{n_0 - 1} \end{array} \right. \quad (4)$$

c is the curvature, k the conic constant, mod is the modulo operation, λ_0 is the central wavelength and $H_{Fresnel}$ is the etching depth of a first order Fresnel lens. In the case of a GRIN Fresnel lens, $H_{Fresnel}$ correspond to the index variation so:

$$\Delta n_{Fresnel} = \frac{\lambda_0}{n_0 - 1} \quad (5)$$

By using this Eq. 4 and Eq. 5, the Fresnel lens is modeled in Zemax and optimized for the camera specifications. Only one channel is modeled and represented *Figure 3* because each channel is the same with a small adaptation of the etching depth as a function of the central wavelength of the filter.

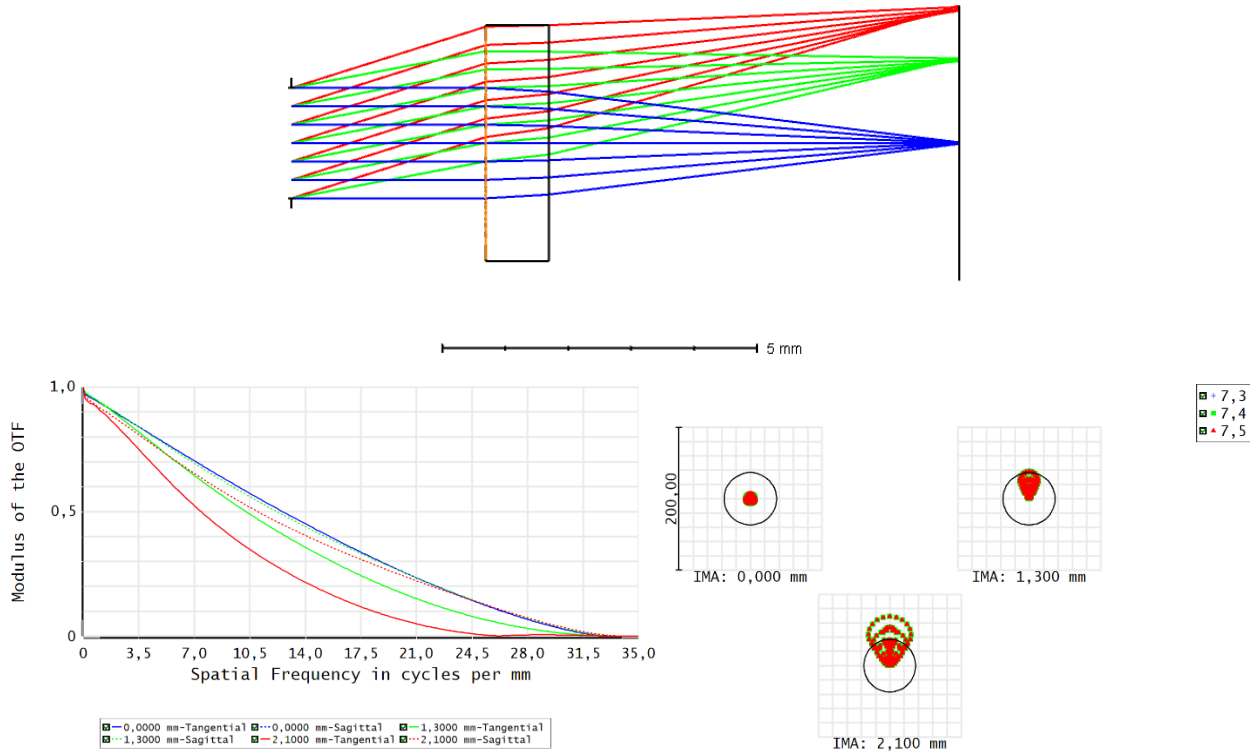


Figure 3. Zemax simulation of a Fresnel lens. On the left, the Modulation Transfert Function (MTF). On the right, the spot diagram given for three different field of view (0° , 10° and 20°).

From the results given by Zemax modelling, we can deduce the GRIN profile of our GRIN Fresnel plate. With the material $75(GeS_2)-15(In_2S_3)-10(CsCl)$ used in the $[7,3 ; 7,5] \mu m$ bandwidth, we obtain a GRIN lens with a diameter of $3,696 mm$ and conic constant of $-3,602$. This GRIN Fresnel lens is composed of 31 rings with the outer ring has a thickness of approximately $30,7 \mu m$.

The laser direct writing technique will discretize the profile into several index levels so we need to determine a compromise between the imaging quality of the Fresnel plate and the spatial resolution of the writing technique. For a first order Fresnel lens as here, we can define the diffraction efficiency as a function of the index versus wavelength variation (Eq. 6) [3].

$$\begin{cases} \eta_{m,\lambda}^N = \text{sinc}^2[\alpha(\lambda) - 1] \text{sinc}^2 \left[\frac{\alpha(\lambda)}{N} \right] \\ \alpha(\lambda) = \frac{\lambda_0}{\lambda} \frac{n(r, \lambda)}{n(r, \lambda_0)} \end{cases} \quad (6)$$

λ_0 is the reference wavelength, N is the number of discretization levels. $n(r, \lambda)$ is the index at the radial position r and the wavelength λ .

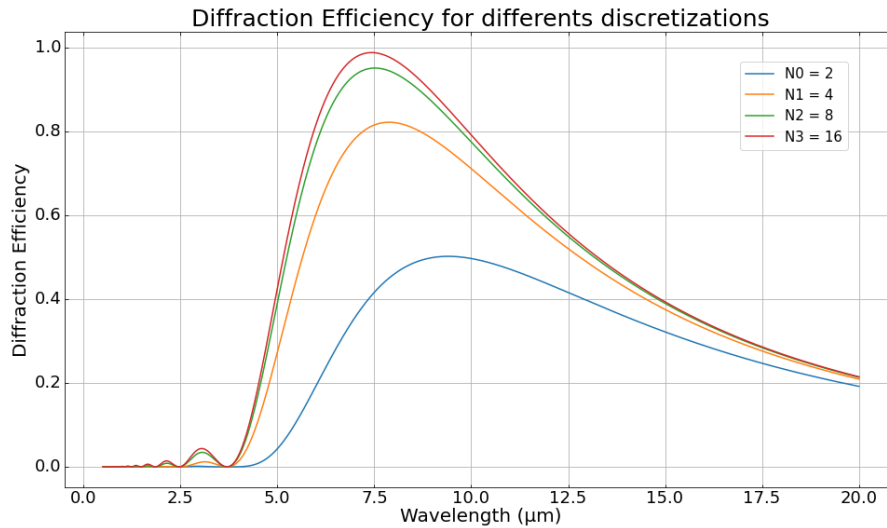


Figure 4. Graphic representation of the diffraction efficiency as a function of the wavelength for a first order Fresnel lens. The chromatic dispersion is disregarded: $n(r, \lambda) = n(r, \lambda_0)$.

Figure 4 shows a good diffraction efficiency (up to 90% for the $[7.3 ; 7.5]\mu\text{m}$ spectral bandwidth) for a first order Fresnel lens discretized in 8 index levels. 16 levels of discretization could be better, but we would have rings thinner than $1 \mu\text{m}$, which cannot be reached with our laser direct writing technique.

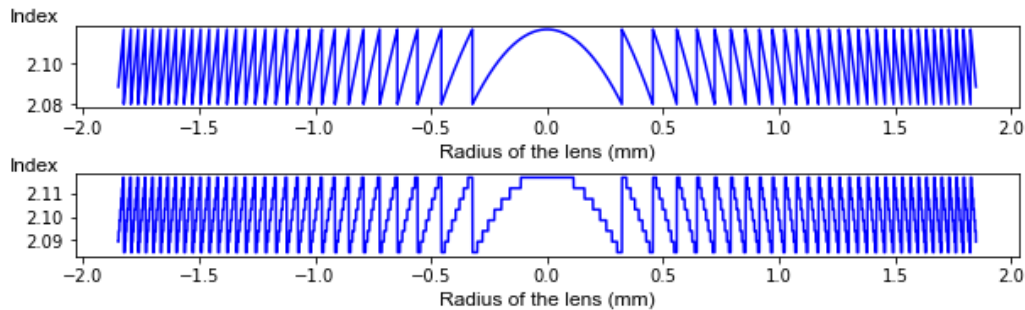


Figure 5. Index profile of the GRIN Fresnel lens for one of the chalcogenide glass ($75(\text{GeS}_2)\text{-}15(\text{In}_2\text{S}_3)\text{-}10(\text{CsCl})$): blazed on the top and discretized on the bottom.

We modeled a GRIN Fresnel lens in our material, which is presented in Figure 5. The total gradient index is about $3,7 \cdot 10^{-2}$ in the material which is reachable with our laser writing technique. With the numerical aperture specification of the camera, the last ring needed is about $30,7 \mu\text{m}$ thick and so the needed spatial resolution is $3,8 \mu\text{m}$.

3. FEMTOSECOND LASER DIRECT WRITING OF GRADIENT INDEX

3.1 Identification of permanent modifications in glasses

The laser-material interaction must be characterized to be able to reproduce the index profile shown in Figure 5. Different materials were studied but only one will be presented in this paper. A comparison of different materials (chalcogenide, germanate and lead-silicate) will be discussed in another paper. There are different types of permanent modifications due to laser writing. First, the type I modification is a permanent isotropic index change due to a local volume variation [11]. The second type of effect appears often with a higher laser energy than the first one but disappears also with a lower laser energy. This type II corresponds to a permanent anisotropic index change associated to the formation of nanogratings [12]. The neutral axis of the birefringence created depends on the laser polarization. The last type of permanent change in the material is the heat accumulation which appears with high energy. The phenomenon is the same as type I but there is a melting and quenching of the matter causing an increase of the line size bigger than the laser spot ones.

For a GRIN Fresnel fabrication, we are especially interested in type I modifications. We want the smallest line size, for a better spatial resolution, and a huge index variation. Several parameters, such as laser frequency, pulse duration, pulse energy or scanning speed can influence the index variation type. *Figure 6* shows the appearance of different types of modification as functions of writing speed and laser energy.

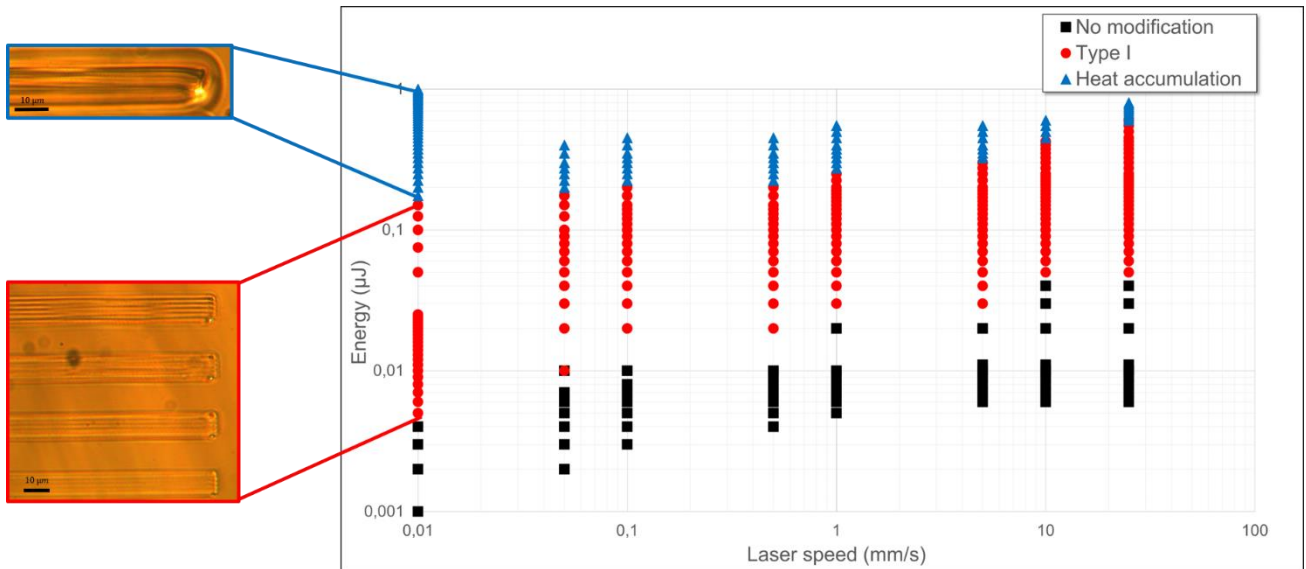


Figure 6. Threshold identification in the $75(\text{GeS}_2)\text{-}15(\text{In}_2\text{S}_3)\text{-}10(\text{CsCl})$ material as a function of laser energy and writing speed. These values were found with a pulse duration of 800 fs and a frequency of 100 kHz .

As shown in *Figure 6*, the faster the writing is the higher is the energy needed to write a permanent change into the substrate. We note that our material has a huge range of energies leading to type I changes even for high writing speed (up to 25 mm/s). It confirms that femtosecond laser direct writing is able to write GRIN optics very quickly. The heat accumulation could also be a way to increase the index variation and to write lines bigger than the laser spot ones enabling faster writing for big surfaces irradiations.

3.2 Phase variation with laser energy and writing speed

GRIN Fresnel optics are more easily described with their phase variation than with their index variation because Fresnel optics are defined by a phase variation $\Delta\varphi = 2\pi\text{ rad}$ for a first order Fresnel lens. To write a GRIN Fresnel plate, we needed to know the precise phase variation implied by the laser as function of the speed writing and the laser energy. So, several laser-written tracks were made at different energies and speeds in the type I range. These tracks were then studied with a Quantitative Phase Measurement (QPM) technique [13]. This technique, described in *Figure 7*, consists in using the transport of intensity equation (TIE) which relies on intensity variation and phase variation. Using an optical microscope, a set of images was taken: one in-focus and two very slightly (a few microns) positively/negatively defocused [14]. A phase image given by QPM of a laser-written simple track is shown in *Figure 7*.



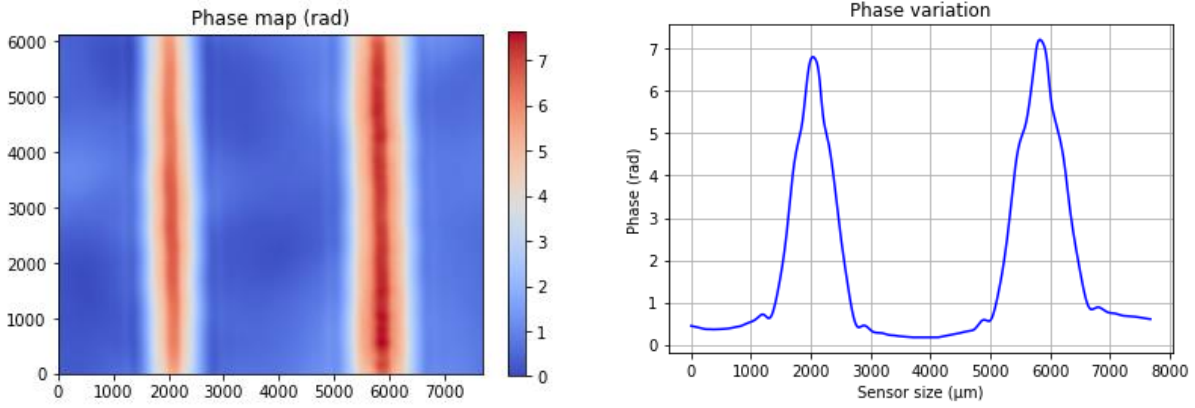


Figure 7. On the top, the system used for Quantitative Phase Measurement (QPM) with a microscope defocused with a piezoelectric actuator. On the left, a phase map of laser-written tracks obtained by QPM. On the right, the horizontal cross-section of this phase map.

To write circular lenses or circular objects like mono-phase discs, a spiral trajectory technique was used. Presented in *Figure 8*, the writing has a tight step of only $1\ \mu\text{m}$ avoiding any groove appearance. Several laser-written linear tracks were made for study with different energies because they are easy to write and to study, but the writing of some discs with a spiral trajectory technique gave us some different results. In fact, it seems that with a spiral technique, a layering of the tracks was responsible of an increase of the phase variation. In order to make GRIN Fresnel lenses, it was important to know the precise phase variation especially in this layering case.

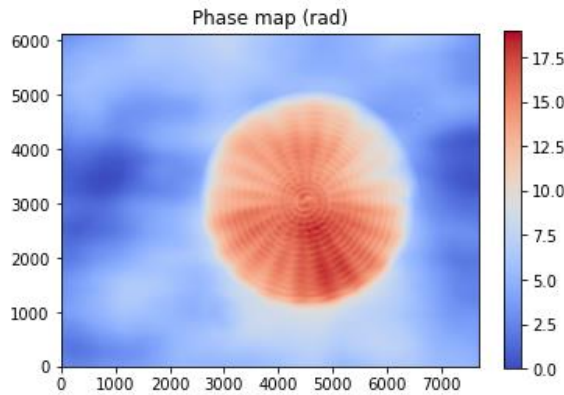


Figure 8. Phase map of a laser-written disc. The diameter of the disc is $100\ \mu\text{m}$ and was written with a $1\ \text{mm/s}$ scanning speed.

The *Figure 8* shows the technique capability to write a huge phase variation into a material even at $1\ \text{mm/s}$ scanning speed. A higher speed is not precise enough with our setup: the shutter is too slow to have a precise beginning. Therefore, we use only this $1\ \text{mm/s}$ writing speed.

3.3 Optical losses pre and post irradiations

Another important characterization needed before the writing of a Fresnel lens is the comparison of optical losses pre and post laser irradiation. If our femtosecond laser direct writing technique create a lot of losses, it would be inappropriate to make an infrared imaging system. So we decided to measure the optical transmission of our material before and after writing a disc of $\pi\ \text{rad}$. Two spectrophotometers were used to measure the all IR band: an UV-Vis-NIR spectrophotometer ($0,2 - 2,5\ \mu\text{m}$) and a FTIR spectrophotometer ($2 - 20\ \mu\text{m}$). The discs written in our material had a $1,5\ \text{mm}$ diameter to be easily measured. The *Figure 9* represents the spectral transmission of the $75(\text{GeS}_2)\text{-}15(\text{In}_2\text{S}_3)\text{-}10(\text{CsCl})$ material pre and post irradiation. We remark that the difference before and after irradiation is negligible. The writing of a disc of $\pi\ \text{rad}$

doesn't affect the transmission. That confirms the capability of this femtosecond laser direct writing technique to make a GRIN Fresnel plate.

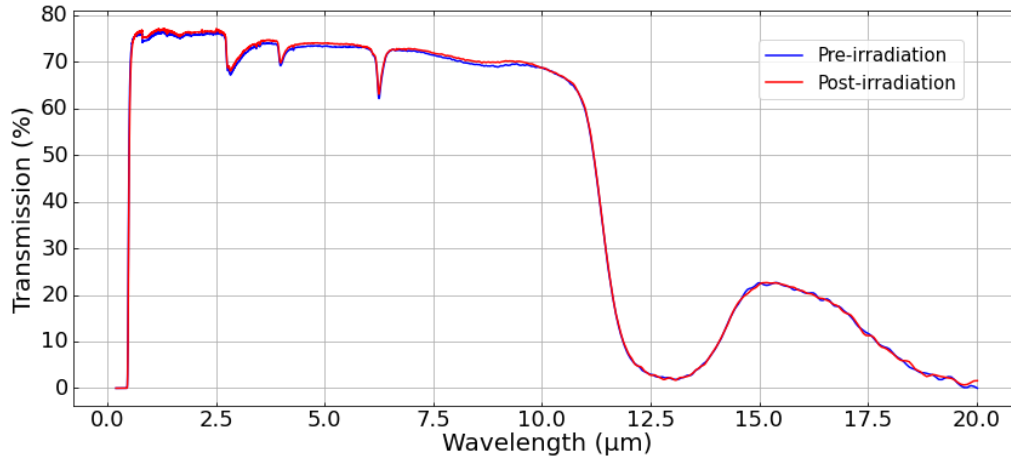


Figure 9. Transmission of the different materials before and after writing a 1,5 mm diameter disc with a phase variation of π rad in the $75(\text{GeS}_2)\text{-}15(\text{In}_2\text{S}_3)\text{-}10(\text{CsCl})$ material.

4. CONCLUSION

In this article, we demonstrated the interest of using gradient index optics and especially gradient index Fresnel lenses to simplify an IR multispectral camera. With a GRIN Fresnel lenses matrix written in a plate, we can reduce the size and the weight of optics integrated in a dewar cooler assembly by fusing GRIN Fresnel lenses inside the array of filters. The femtosecond laser direct writing technique has demonstrated the possibility to make quickly these GRIN Fresnel lenses in a chalcogenide material. Some more trials are necessary to write a first GRIN Fresnel prototype as for instance some experiment concerning movement control. Within future work, we plan to make a first prototype using these GRIN optics and assess its performances experimentally.

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