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FEMTOSECOND LASER DIRECT WRITING OF A GRADIENT INDEX FRESNEL LENS 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.

This work presented takes advantage of recent techniques in femtosecond laser direct writing to imprint optical systems. Here we want to simplify an infrared multispectral imaging system, which combines a lens array and a filter array. Each channel has a focal length of 7 mm and a f-number of 4.

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.

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 2x2 lenses with a focal length of 7 mm and a F-number of 4. Each channel has a field of view of 40°x30° and forms a 320x256 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 300 nm.

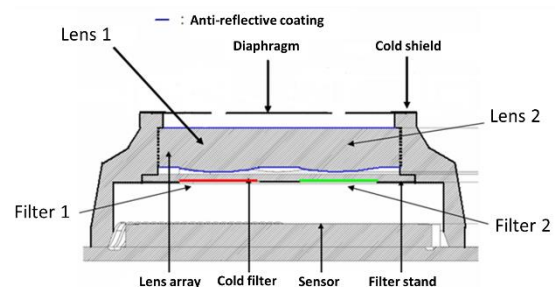


Figure 1. Cross-section of the ONERA multispectral camera. From top to bottom, the diaphragm, the lens array, the filter array and the sensor.

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 depose 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 [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 a short focal length as the focal length of the studied camera needs an important index variation. For a 7 mm focal length in our case, this type of design needs a gradient index with a maximum variation of $\Delta n = 0,11$ for a thickness of 1 mm that is higher than what a femtosecond laser direct writing can create. One of the maximum index variation reached today in mid-IR components with the femtosecond laser writing technique is about 0.05 in As_2S_3 (a chalcogenide glass) [9].

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.

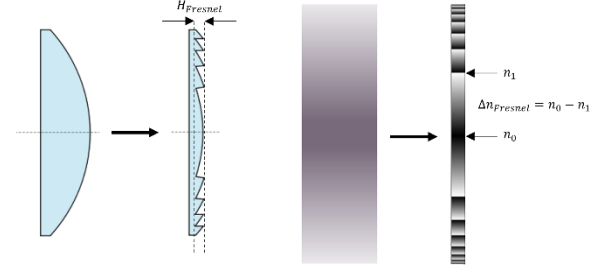


Figure 2. From a classical lens to a Fresnel lens and from a GRIN lens to a GRIN Fresnel lens.

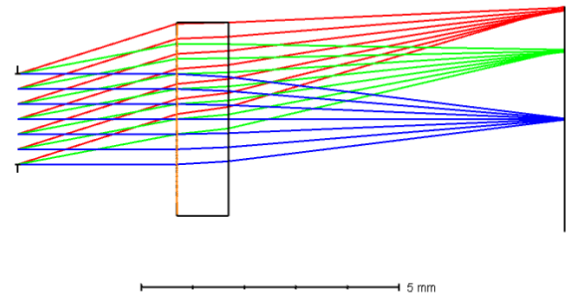
Given that a GRIN index profile is equivalent to a surface sag of a conventional lens, the modeling of a Fresnel lens can be done in the Zemax software with a “User Define Surface” created for conventional Fresnel lenses. The surface sag used in the software is then converted into an index profile distribution. The surface sag ($z_{Fresnel}$) equation is described in Eq. 3 [10].

$$\begin{cases} z_{Fresnel}(r) = \frac{cr^2}{1 + \sqrt{(1 - (1 + k)c^2 r^2}}} \text{ mod } H_{Fresnel} \\ H_{Fresnel} = \frac{\lambda_0}{n_0 - 1} \end{cases} \quad (3)$$

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, the surface sag is replaced by an index profile distribution ($n_{Fresnel}$) and so $H_{Fresnel}$ corresponds to the total index variation $\Delta n_{Fresnel}$:

$$\begin{cases} n_{Fresnel}(r) = \frac{cr^2}{1 + \sqrt{(1 - (1 + k)c^2 r^2}}} \text{ mod } \Delta n_{Fresnel} \\ \Delta n_{Fresnel} = \frac{\lambda_0}{n_0 - 1} \end{cases} \quad (4)$$

By using these Eq. 3 and Eq. 4, the Fresnel GRIN lens is modeled in Zemax and optimized for the camera specifications. Only one channel is modeled and represented in Figure 3 because each channel is the same with a small adaptation of the total index variation as a function of the central wavelength of the filter.



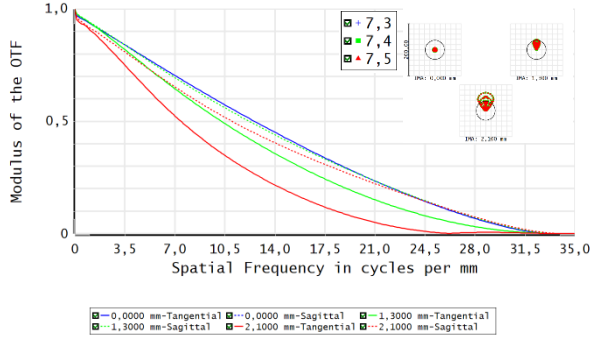


Figure 3. On the top, Zemax 2D layout of a Fresnel lens. Below, the Modulation Transfer Function (MTF) and the spot diagram given for three different field of view (0° , 10° and 20°).

From the results given by Zemax modelling, we can deduce the GRIN profile of our GRIN Fresnel plate. With the material $75(\text{GeS}_2) - 15(\text{In}_2\text{S}_3) - 10(\text{CsCl})$ used in the $[7,3 ; 7,5] \mu\text{m}$ bandwidth, we obtain a GRIN lens with a diameter of 3.7 mm and conic constant of -3.6 . This GRIN Fresnel lens is composed of 31 rings with the outer ring has a width of approximately $30.7 \mu\text{m}$.

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. 5) [3].

$$\begin{cases} \eta_{m,\lambda}^N = \text{sinc}^2[\alpha(\lambda) - 1] \text{sinc}^2 \left[\frac{\alpha(\lambda)}{N} \right] \\ \alpha(\lambda) = \frac{\lambda_0 n(r, \lambda)}{\lambda n(r, \lambda_0)} \end{cases} \quad (5)$$

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 .

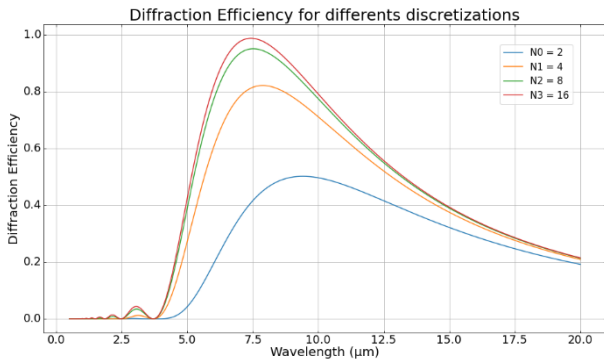


Figure 4. Graphic representation of the diffraction efficiency as a function of the wavelength for a first order Fresnel lens. The chromatic dispersion is disregarded: $n(r, \lambda) = n(r, \lambda_0)$.

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.

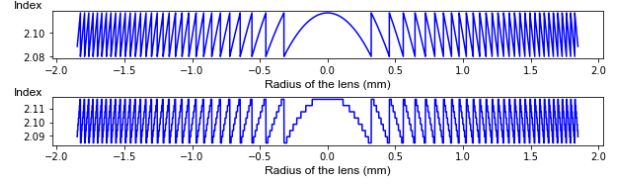


Figure 5. Index profile of the GRIN Fresnel lens made in the chalcogenide glass $75(\text{GeS}_2) - 15(\text{In}_2\text{S}_3) - 10(\text{CsCl})$: blazed on the top and discretized on the bottom.

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 we need a spatial resolution of $3.8 \mu\text{m}$ to be able to write this last ring discretized into 8 levels.

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. We studied the chalcogenide glass $75(\text{GeS}_2) - 15(\text{In}_2\text{S}_3) - 10(\text{CsCl})$. 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 (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.

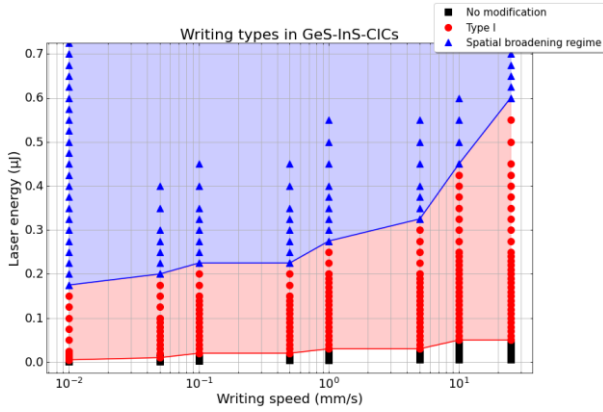


Figure 6. Threshold identification in the $75(\text{GeS}_2) - 15(\text{In}_2\text{S}_3) - 10(\text{CsCl})$ material as a function of laser energy and writing speed. These values were found with a pulse duration of 800 fs and a frequency of 100 kHz.

As shown in Figure 6, the faster the writing is the higher the energy needed is 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 discs were made at different energies and speeds in the type I range. To write circular lenses or circular objects like monophasic discs, a spiral trajectory technique was used. Presented in Figure 7, the writing has a tight step of only $1 \mu\text{m}$ avoiding any groove appearance. These discs were then studied with a Quantitative Phase Measurement (QPM) technique [13]. This technique 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 disc is shown in Figure 7.

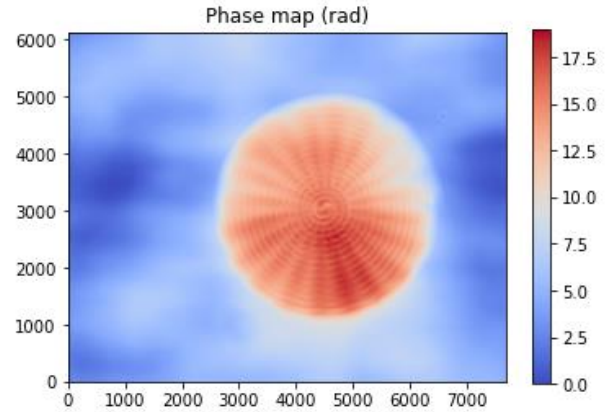


Figure 7. Phase map of a laser-written disc. The diameter of the disc is $100 \mu\text{m}$ and was written with a 1 mm/s scanning speed.

Figure 7 illustrates the technique capability to write a huge phase variation into a material even at 1 mm/s scanning speed. Higher writing speeds were tried (up to 2.5 mm/s) with success but a dedicated setup would be more appropriate for accurately writing complex shapes. Therefore, we use only this 1 mm/s writing speed.

For many applications it would be necessary to convert phase variation ($\Delta\varphi$ in rad) into refractive index changes written by the femtosecond laser. In this view, it is sufficient to measure the thickness of the laser-modified region d to have an approximation of the index variation:

$$\Delta n = \frac{\lambda}{2\pi d} \Delta\varphi \quad (6)$$

λ is the wavelength used for the quantitative phase measurement. Thus the index variation implemented by the fs-laser in the Figure 7 is about 2.7×10^{-2} .

3.3. Optical losses pre and post irradiation

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 creates 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 which introduces a phase variation 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 mm diameter. The Figure 8 represents the spectral transmission of the $75(\text{GeS}_2) - 15(\text{In}_2\text{S}_3) - 10(\text{CsCl})$ 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.

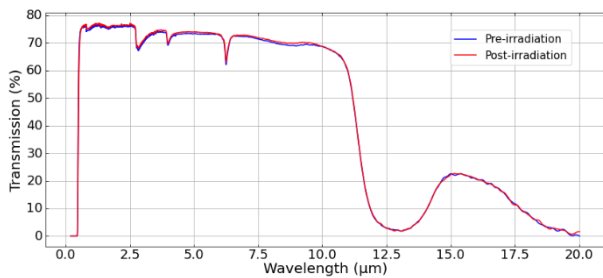


Figure 8. Transmission before and after writing a 1,5 mm diameter disc with a phase variation of π rad in the $75(\text{GeS}_2) - 15(\text{In}_2\text{S}_3) - 10(\text{CsCl})$ material.

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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