Ultrafast Laser Inscription of High Performance Mid-Infrared Waveguides in Chalcogenide Glass

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We present the realization of mid-infrared waveguide by ultrafast laser inscription technique in a chalcogenide glass. Our approach is based on multicore waveguide that consists in an alignment on a mesh of positive refractive index channels placed parallel to each other. Two different meshes are investigated with different refractive index contrasts between the channel and the glass matrix. A detailed analysis of the performances at a wavelength of 4.5 μm shows propagation losses of 0.20 ± 0.05 dB/cm and coupling efficiencies higher than 60%.

I. INTRODUCTION

In the mid-infrared (mid-IR) spectral range, between 2 and 25 μm, most of the molecules have strong absorption peaks that can be used to selectively and efficiently detect and quantify chemical or biological species. This is the reason why large-scale projects are currently developing around mid-infrared photonics for various applications directly concerning important societal issues like health and environment monitoring or security [1–4].

The extension of silicon technology to higher wavelengths is a natural way to make mid-IR photonic components. However silicon oxide that is used in this technology, rapidly limits the possible wavelength range since it starts to absorb around ~3.6 μm [5]. Therefore technical solutions to minimize the amount of light propagating in the SiO₂ layer should be developed. A first approach is to modify the geometry of the guides to minimize contact between the core and the absorbing layer, for example, by suspending them [6] or placing them on a pedestal [7]. The obtained propagation losses are below 1 dB/cm (0.82 dB/cm precisely) in the case of suspended waveguide and 2.7 dB/cm in the case of pedestal use but both of these results are obtained for a wavelength below 4 μm. An other strategy more suitable for higher wavelengths is to modify the material. For an example silicon on sapphire nanowires have shown propagation losses of 2 dB/cm at λ = 5.18 μm [8] and 1 dB/cm at λ = 4 μm [9]. On the other hand germanium-based materials seem to be very promising especially for high wavelengths although currently the level of propagation losses remains above 1 dB/cm [10–13]. Moreover the small physical dimensions of the transverse section of those waveguide preclude efficient light collection and coupling losses of several decibels are often reported.

Another way to obtain a waveguide beyond 4 μm is to make it by ultrafast laser inscription (ULI) technique in glass. The ULI is a very versatile and cost-effective method for rapid prototyping and production of optical components [14]. It has been applied in the mid-IR to different chalcogenide glasses (gallium lanthanum sulfide and 75GeS₂-15Ga₂S₃-4CsI-2Sb₂S₃-4SnS in [15] and Ge₁₅As₁₅S₇₀ in [16]) and guiding up to λ = 10 μm has been experimentally demonstrated. Very recently propagation loss around 1-1.5 dB/cm has been reported at λ = 7.8 μm in an other germanium based composition (Ge₃₃As₁₂Se₅₅) [17].

We have previously reported a writing procedure of multicore waveguide in an arsenic-free germanium based chalcogenide glass (72GeS₂-18Ga₂S₃-10CsCl) that shows propagation loss of 0.11 ± 0.03 dB/cm at λ = 1.55 μm [18]. In this letter we presents the extension of these results to the mid-IR at λ = 4.5 μm.

II. DESCRIPTION OF THE WRITING PROCEDURE

The photowritten waveguides are multicore type and they consist of channels of positive refractive index variation (∆n) induced by a train of femtosecond pulses, placed parallel to each other on a mesh. Here the inscription geometry differs from the classical transverse or longitudinal ones as the irradiation is done without continuous sample translation. In a first step the laser beam is focused in front of the channel ⊹ and the sample is irradiated with a burst of femtosecond pulses. The duration τ of this burst is an important parameter of the experiment as it will be described later. The result of this irradiation is an increase of the length of the channel ⊹. In a second step the sample is translated perpendicularly to the writing direction in the plan of the transverse section so that the channel ⊹ is in front of the focus of the laser beam. A second burst of pulses is sent over the sample which again increases the channel length. The operation is repeated as needed for all the channels until the slice of transverse section is completed. Then the sample is translated parallel to the writing beam and the procedure is repeated over the entire length of the sample.

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This procedure presents the advantage that the magnitude of the refractive index contrast between the channel and the non-irradiated matrix can be easily controlled by varying the duration of the burst $\tau$. We have measured $\Delta n$ using quantitative phase microscopy followed by an Abel inversion [19] and its dependency with $\tau$ is presented on the figure 1 for different repetition rates of the pulse train. It can be seen from this figure that $\Delta n$ increases nearly linearly for $\tau$ values below 150 ms and saturates for higher values. Also the level of saturation depends on the repetition rate, which can be attributed to the phenomenon of accumulation of charges released during the writing process [20].

Figure 1. Dependency of the refractive index contrast between the individual channel and the glass matrix for different repetition rate of the pulse train. The dashed lines are a guide for eye.

On the other hand, the diameter of the individual channels is constant due to the formation process of $\Delta n$. Indeed, the refractive index variation is related to the formation of a filament during the propagation of the femtosecond pulse in the glass, whose diameter is defined by the properties of the material [20]. The thermal effects that could induce a dependence of the diameter of the inscription with the experimental parameters [21], are not dominant in the process of appearance of $\Delta n$. However it is possible to adjust the diameter of the total structure by changing the distance between the channels or by adding others. Therefore it is possible to select independently $\Delta n$ and the dimension of the waveguide in order to engineer its characteristics as needed.

III. WAVEGUIDE PERFORMANCE MEASUREMENTS

First we study the case of waveguide composed of channels placed on a hexagonal mesh and two configurations are compared. They differ in the number of rows that make up the structure. The first is composed of 4 rows of channels separated by a distance of 2.875 $\mu$m and the second by 5 rows with a separation of 2.3 $\mu$m between the channels so that the total diameter of the structure is the same (23 $\mu$m). A typical example of such structure is represented on the inset of the figure 2. The waveguides are written with a laser repetition rate of 200 kHz.

![Figure 2. Measured propagation losses for hexagonal mesh structures with 4 and 5 rows. The dashed lines are a guide for eye.](image)

The propagation losses are measured according to the back reflection method [22]. After the inscription the sample is cut and repolished to eliminate edge effects. The input face is cut at a slight angle to the cross section plane of the guides in order to spatially separate the reflected waves on the input and the output face of the waveguide and thus eliminate interference likely to distort measurements. Their total length after this step is equal to 28 mm. The results of the loss measurement are shown in the figure 2. The existence of an optimal irradiation duration value $\tau_{\text{min}}$ that leads to a minimum of propagation losses $\alpha$ is clearly observed. This minimum value ($\alpha_{\text{min}}$) is equal to 0.20 $\pm$ 0.05 dB/cm, which is far below the values obtained for photowritten waveguides or those derived from silicon photonics in the mid-IR. In fact for $\tau < \tau_{\text{min}}$ the beam is poorly confined in the structure whereas for $\tau > \tau_{\text{min}}$ the field tends to be localized into the individual channel. The optimal condition is a compromise between these two situations [18].

It is interesting to note that $\alpha_{\text{min}}$ is the same for the two configurations (4 and 5 rows). This means that it is independent of the density of individual channels, i.e. the number of channels per square micron, since the surface of the transverse section is the same for both configurations. Of course it will not be the case if the distance between the channels becomes too large (i.e. structure with 2 or 3 rows, considering the same total diameter of written structure). Therefore it is a good indication that our writing method leads to very homogeneous refractive index variation channel and that the concatenation of the different slices of transverse section does not add irregularities that would scatter the light similarly to side roughness. However for a 4 rows structure with a lower density (0.177 channels/$\mu$m$^2$ compared with 0.265
channels/µm² in the case of 5 rows) the optimal value of τ becomes more critical since the dependence of α over the burst duration τ is more pronounced.

It should be noted that all of these guides, and those described later in the text, were written in the same piece of glass. Thus the properties of the host matrix, which could influence the performance, are the same for all waveguides and the differences between the behaviors of the propagation losses are due only to the different structures of the transverse section.

Figure 3. Measured propagation loss for circular mesh structure with 5 rings. The dashed line is a guide for eye.

To illustrate the versatility of our method we modify the morphology of the transverse section of the waveguide. Here the mesh is composed of concentric rings. On the Nth ring the channels are separated by an angle 2π/6N. Here the inscriptions were made with a laser repetition rate of 250 kHz. Indeed, preliminary evaluations carried out with a rate identical to that used for the hexagonal mesh, have shown that higher values of Δn are necessary to obtain minimum losses. A photograph of a structure formed of 5 rings is shown in the inset of the figure 3 that presents the propagation losses for different burst durations. On this figure we can see that the behavior of α with τ is the same as for a hexagonal mesh and that the minimum value is the same within the uncertainties of the measurements. Here also, we can observe that the decrease in the Δn channels density (0.219 channels/µm²) leads to a stricter dependence of propagation losses with the duration of the pulse burst compared with the hexagonal mesh with 5 rows.

We can now consider the other sources of losses but before we note that the intrinsic absorption of the bulk material is already taken into account in the measurement of the propagation losses. First of all the reflection coefficient at the air-guide interfaces was measured as being in the order of 13%, which is in agreement with the value of the refractive index of the sample [23]. We also measured the power carried by the waveguide and derived the coupling efficiency using the following equation:

\[
\eta = \frac{1}{(1 - R)^2 T_{Opt}} \frac{P_{Out}}{P_{In}} 10^{(0.1 \alpha L)}
\]

where \( R \) is the reflection coefficient from the interface between air and the waveguide, \( T_{Opt} \) is the transmission coefficient of the focusing and collimating optics, \( \alpha \) is taken from the values reported in the figures 2 and 3, \( L \) is the length of the waveguide (28 mm) and \( P_{In} \) and \( P_{Out} \) are the powers measured before and after the waveguide, respectively.

Figure 4. Coupling efficiency of light inside the waveguides for the hexagonal and circular meshes.

The results of these measurements are reported on the figure 4. For all the considered structures the coupling efficiency \( \eta \) is an increasing function of the burst duration, i.e. Δn, with values that can be higher than 0.6. However if the behavior of the dependence is the same for all meshes, we note that for most of the values of τ, the highest value for \( \eta \) is obtained for the 5 rows hexagonal mesh that corresponds to the structures with the highest density of Δn channels.

It should be remarked that the global performance of the waveguide being a combination of both the propagation loss and the coupling efficiency, the value of τ that gives the lowest value of α could be not the optimum one since a higher value would increase \( \eta \) and at last, leads to a maximized carried power. Consequently τ should be chosen according to the functionality of the device. For a short one it would be preferable to select large τ to maximize \( \eta \) while if the length is so that the propagation losses are predominant, τ should be shorter to minimize \( \alpha \).

Finally the near field pattern of the propagated beam was imaged on the InSb sensor of a mid-IR camera (FLIR A6750sc) and the mode has been measured for the optimum values of the burst duration τ. As it can be seen from the figure 5 the beam profile is very close to be Gaussian indicating the single mode behavior of the waveguide. On this figure one can see the mode corresponding to a hexagonal mesh with 5 rows but similar profiles are obtained for the others structures.
IV. CONCLUSIONS

In conclusion we present the realization of mid-IR waveguides in arsenic free chalcogenide glass with propagation loss below 0.2 dB/cm at 4.5 µm. Moreover our method allows a control of the waveguide dimensions meaning that an efficient light collection can be achieved in most situations as the diameter of the structure can be adapted according to the requirement, i.e. butt coupling from a fiber or coupling from free space. As an illustration we are able to achieve in the best configuration a total power carried corrected for Fresnel losses is as large as 60% of the incident power (we do not take into account Fresnel loss since it can be minimized by using an anti-reflective coating). By combining these results with those obtained previously [18] this demonstrates that the described method can be used to design waveguide devices with high performances over the whole range between 1.5 and 4.5 µm. It can be objectively assumed that this range can be extended to higher wavelengths and that the ultimate limit would be defined by the transmission of glass (10 µm). This work is currently being continued to extend this technique to the production of curved guides.

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