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# Femtosecond laser fabrication of gradient refractive index micro-lenses in chalcogenide glass for applications in visible and infrared region

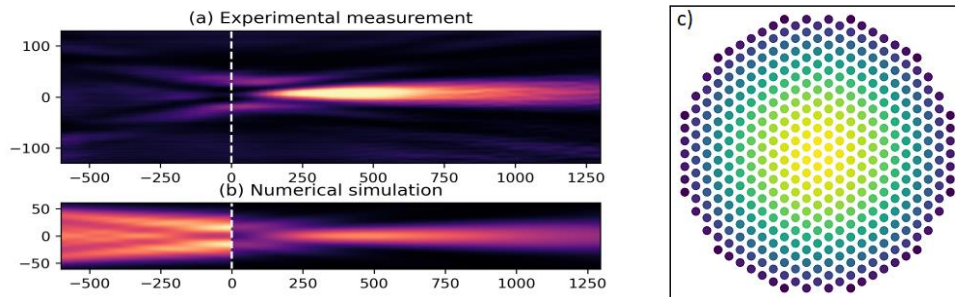
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Gradient refractive index (GRIN) lenses are optical components having spatial variations of refractive index in the material [1]. GRIN lenses have been widely used for several applications such as the correction of optical aberrations [2], fiber coupling [3], imaging systems [4]. Many techniques have been developed for the fabrication of GRIN lenses: chemical vapor deposition, ion exchange or neutron irradiation [5]. However, these techniques cannot be applied for all materials because their use depends of the composition [6]. In addition, the femtosecond laser direct writing (FLDW) method is a very flexible technique to modify the refractive index of materials. This powerful method allows controlling the inscribed shape [6], especially in the scale of  $\mu\text{m}$ . In this work, we focus on the fabrication of GRIN micro-lenses in chalcogenide glasses (ChG) using this FLDW method.

The GRIN micro-lenses were fabricated by irradiating the ChG substrate under a focused femtosecond laser beam. The focused laser beam can reach very high intensity and lead to the local modification of the refractive index of the material in the focal volume. The sample was displaced along the propagation direction of the laser beam on a hexagonal mesh to form parallel channels. By varying the irradiation time of each channel, we can create a different amplitude of the refractive index contrast among the channels and the glass which form a structure with a controlled refractive index profile (Fig.1(c)). A parabolic refractive index profile structure was used to realize the GRIN micro-lenses. The characterization of those micro-lenses was performed at two different wavelengths of  $2.3\ \mu\text{m}$  and  $4.5\ \mu\text{m}$ . The laser sources were spatially filtered and expanded to have flat wavefront incident onto the samples. The focal spot of the micro-lenses was imaged by a lens and a camera which were mounted on x-y translation stages. To obtain the data about the focal region, the imaging lens and the camera were displaced step by step through the focal region of the micro-lenses along the propagation direction of the laser sources. Then the focal regions of the micro-lenses were reconstructed based on the images recorded by the camera. Numerical simulations using finite difference time domain (FDTD) method also were performed and are well agreed with the experimental results as shown in Fig.1(a) and (b).



**Fig. 1** The cross sections of the focal volume in xz plane obtained from (a) experimental measurement and (b) numerical simulation of a  $120\ \mu\text{m}$  diameter micro-lens under the illumination of a laser source at  $4.5\ \mu\text{m}$  wavelength. (c) Refractive index profile of a GRIN micro-lens, the value of refractive index increases from the edge to the center of the micro-lens.

The working distances of micro-lenses with different diameters ( $60 - 120\ \mu\text{m}$ ) have been measured and they spread from 0 to several hundred of  $\mu\text{m}$  following the decrease of the sample thickness.

Using the FLDW method, we realized various GRIN micro-lenses in the volume of ChG with good optical qualities. The methodology developed in this study could also be applied for the fabrication of other micro-optical components such as axicons or cylindrical lenses.

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