Beam self-action in planar chalcogenide waveguides

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ABSTRACT

We present a new experimental technique based on the analysis of beam self-action to measure optical nonlinearity in planar waveguides. This technique is applied to analyze the nonlinear properties of slab chalcogenide waveguides that can develop Kerr induced self-focusing or self-defocusing, depending upon the waveguide structure and composition. Optical nonlinearity in chalcogenide waveguide is studied in the 1200 nm to 1550 nm wavelength range in femtosecond regime. Results of the proposed technique compare favorably with n_2 values obtained with the Z-scan technique. In addition, beam self-trapping in the chalcogenide waveguides due to material photosensitivity is also observed.

Keywords: Nonlinear optics, Chalcogenide waveguides, Beam self-action, Kerr effect, Spatial soliton, Photosensitivity

INTRODUCTION

Nonlinear optical materials have attracted great interest, both from the fundamental and the applied points of view. Different techniques such as two-photon absorption spectroscopy, wave mixing, third-harmonic generation, nonlinear interferometry, optical Kerr shutter or self-phase modulation, have been developed to measure the Kerr non-linear refractive index as well as the non-linear absorption coefficients[1]. The most familiar technique is the Z-scan technique which is appropriate to measure bulk or thin materials [2]. However to study nonlinear properties in very thin layers that form planar waveguides, other techniques have to be used. We propose a technique based on the analysis of beam self-action and more specifically on beam self-trapping which can overcome the limitation of Z-scan. Self-trapping occurs, when diffraction effect is counteracted by nonlinear index change induced by the beam itself [3]. Such an effect can even lead to the formation of spatial solitons which are beams that propagate without changing their shape. Among the variety of nonlinear materials, chalcogenide glasses are of great interest due to their large Kerr nonlinearity, low losses, low fabrication cost and numerous applications in the infrared region. Intense research activities are going on in planar waveguide structures[7-9,11]and in fibers for application in the infrared region. While bulk chalcogenide properties are fairly well known, characterizations have to be performed when deposited under thin films. Indeed, deposited films often have nonlinear properties that significantly differ from the initial bulk target. Here we report nonlinear studies of planar chalcogenide waveguides via self-trapped beams. This technique is well suited to measure optical nonlinearity in planar waveguides of any composition.

The experiment consists in injecting a pulsed laser in a planar waveguide while the beam profile at the output face is monitored with a camera. Since the launched beam is narrow (typically 10 to 50 µm wide) it clearly enlarges due to diffraction in the linear regime. In the nonlinear regime, i.e. at high power, diffraction is modified due to either self-focusing or self- defocusing[4]. Nonlinear Schrödinger equation that includes absorption is used to model the beam propagation in the planar waveguide. It can be written as,

$$\frac{\partial E}{\partial Z} = - \frac{\alpha_1}{2} - \frac{\alpha_2}{2}\,|E^2|\,E + iK_0 n_2 |E^2|\,E \qquad (1)$$

Where E is the electric field related to the intensity by, $I = |E^2|$. α_1 and α_2 are the linear and two-photon absorption coefficients, n_2 is the Kerr nonlinear coefficient, K_0 is the propagation constant in the medium. The Kerr coefficient (n_2) is deduced by analysis of the output beam profile modification as a function of the injected light power. The experimental results are compared with simulations from the nonlinear Schrödinger equation (1) solved with a beam propagation method (BPM) [4].

The structure of the manuscript is as follow. First, we present results on beam self-action studies in planar chalcogenide waveguides of different compositions. The following section presents the dependence of the optical nonlinearity as a function of wavelength. The last section reports on the photosensitivity of the chalcogenide leading to a beam modification under long illumination time.

Kerr induced beam self-action

In our experiment, we studied structures of Ge-Sb-Se glasses deposited by the radio frequency (RF) magnetron sputtering technique on oxidized silicon wafers. The structure and physicochemical properties were analyzed using micro-Raman spectroscopy and X-ray diffraction. The waveguides thickness and refractive index were characterized by scanning electron microscopy, ellipsometry, and prism coupling technique. Two slab waveguides of different guiding layer thickness (3.5µm, 2µm) and chemical composition respectively, $Ge_{28.3}$ $Sb_{6.8}$ $Se_{64.9}$ and $Ge_{12.1}$ $Sb_{25.5}$ $Se_{62.5}$ were studied. The structure and chemical compositions of the characterized waveguides are very close to the bulk glass target prepared by RF magnetron sputtering [5, 6].

As shown in figure 1, the optical nonlinear measurements were performed using 200 fs laser pulses from a tunable optical parametric oscillator with an 80 MHz repetition rate. The beam was reshaped to an elliptical spot by a cylindrical lens and a X40 microscope objective. The input beam width at 1.55µm is 6 x 42µm (FWHM) in the guided and transverse dimension, respectively. This shaping allowed an efficient coupling and matches appropriately the fundamental guided mode. Input power was varied by the combination of half-wave plate and polarizer. The sample was mounted on an XYZ translation stage. The input coupling was fine-tuned by proper positioning of the waveguide to get the maximum light coupling. Beam profile at the output face of the chalcogenide film is imaged onto a vidicon camera by a X10 microscope objective.

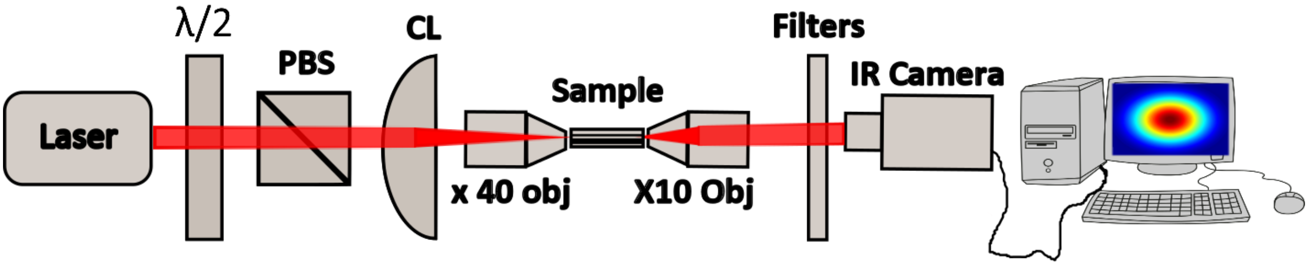

Figure 1.The experimental setup for the study of beam self-action in a planar waveguide. λ/2, half-wave plate; PBS, polarizing beam splitter; CL, cylindrical lens; Obj, microscope objective.

A typical result on beam self-action performed at 1550 nm is presented in figure 2. The sample is a 1.2 cm long slab waveguide made of a 3.5µm thick $Ge_{28.3}$-$Sb_{6.8}$-Se_{64} chalcogenide layer deposited on top of 500 µm thick SiO2/Si wafer substrate by RF magnetron sputtering. The waveguide properties of the chalcogenide were analyzed by prism coupling technique. Linear refractive index of the guiding layer and the SiO2 buffer layer is 2.47, 1.447 respectively. The waveguide effect is possible at the high refractive index guiding layer near the substrate surface. Figure 2a shows the 42 µm wide input beam, which is coupled into the waveguide. At low average power (4mW), the beam diffracts freely and the output FWHM is about 149 µm (fig 2b). At higher power (70mW), we observe a beam narrowing which reveals a positive n_2 coefficient. Further increase of the beam power even leads to the formation of a spatial soliton as depicted in fig (2c). Formation of Kerr spatial soliton is confirmed by comparing the input and output beam profiles. In our case, the soliton is observed for an input intensity of 0.37 GW/cm^2. Numerical representation of time averaged beam evolution corresponding to the soliton propagation is depicted in figure 2d. The intensity dependent changes in refractive index of the medium are attributed to the Kerr effect. Propagation of a shape invariant self-guided optical beam in $Ge_{28.3}$-$Sb_{6.8}$-Se_{64}, makes them suitable for ultrafast switching in telecommunication[7]. Comparison of BPM simulations with the experimental results leads to a nonlinear coefficient n_2 of 11×10^{-18} $m^2.W^{-1}$ with $\alpha_2 = 0.29\ cm/GW$.To evaluate the validity of the proposed technique to deduce the n_2 coefficient, we have compared it the one obtained by Z scan measurements in a bulk chalcogenide of the same composition[5]. The nonlinear Kerr coefficient of bulk obtained by Z scan at 1.55 µm is $8.9 \pm 2.7 \times 10^{-18} m^2.W^{-1}$. The good agreement in the n_2 values shows that the technique based on beam self-action is well-suitable to measure optical nonlinearity in nonlinear slab waveguides of any composition.

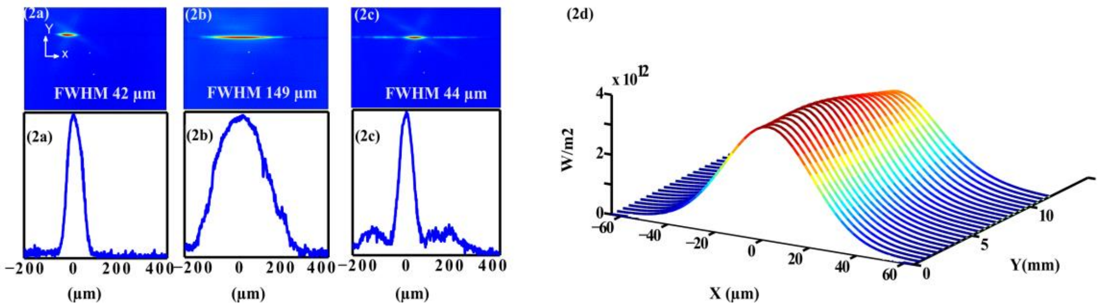

Figure 2: Experimental images and profiles of (2a) Input beam injected in to the planar waveguide (2b) diffracted Output beam in linear regime (2c) Self-trapped beam leading to soliton formation in nonlinear regime of propagation. Numerical representation of time averaged beam evolution corresponding to soliton propagation for an input intensity of 0.37 GW/cm^2 (2d). Material parameters used are λ =1550 nm, n2= 11×10^{-18} m^2.W-1, α_1 = 0.15 cm^{-1}, α_2 =0.29 cm/GW.

In addition to the measurements in $Ge_{28.3}$-$Sb_{6.8}$-Se_{64} films we tested another slab waveguide made of 2 µm thick $Ge_{12.1}$ $Sb_{25.5}$ $Se_{62.5}$ guiding layer at telecommunication wavelength. Our experimental results on beam self-action are shown in figure 3a. Input beam is similar than in previous experiment. At low power the beam broadens to 78µm because of diffraction (see red curve from figure 3a) occurred in the 1 cm long sample. When the input power is increased to 65mw the beam partially focuses to 60µm at the output face (green curve from Figure 3a). This is an intermediate regime where self-focusing is observed at the output face. A further increase of power gives a wider beam compare to the linear regime. This is illustrated by the blue curve, where a beam width of 110 µm is observed for an input beam power of 180mW. This unusual behavior can be explained thanks to the simulation presented in figure 3b.

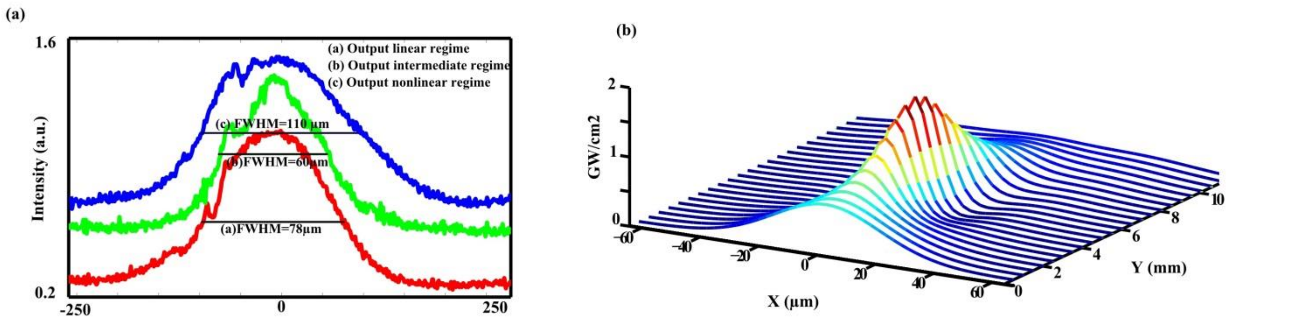

Figure 3: Experimental results showing both self-focusing and self-defocusing in the planar waveguide ($Ge_{12.1}$ $Sb_{25.5}$ $Se_{62.5}$) for varying power (3a). Numerical representation of time averaged beam evolution in agreement with the beam self-action behavior, for an input intensity of 0.678 GW/cm^2 (3b). For λ =1550 nm, n2= 22×10^{-18} $m^2.W^{-1}$, α_1 = 0.15 cm^{-1}, α_2 =0.84cm/GW.

In this sample a larger nonlinear linear two photon absorption ($\alpha_2 = 0.84$ cm/GW) is assumed compare to the previous studied composition because the bandgap energy (1.7eV) is more close to the photon energy (0.8 eV) corresponding to an irradiation at 1550 nm. The bandgap energy of the previous sample ($Ge_{28.3}$-$Sb_{6.8}$-Se_{64}) is 2.11eV. Moreover a larger n_2 coefficient is expected. However the simulation shows that even though clear focusing can be obtained on a short distance this self-focusing effect cannot be maintained because of the nonlinear absorption. Indeed, the beam intensity rapidly decreases and the nonlinear index change is thus no longer sufficient to produce the trapped beam. The self-defocused beam observed at the output face at high power is the consequence of an over focused beam by nonlinear effect that subsequently diffracts almost in linear regime. In the present case, the extracted nonlinear refractive index is 22×10^{-18} $m^2.W^{-1}$. This is in good agreement with the n_2 value measured by the Z-scan techniques in bulk chalcogenide[5].

Optical nonlinearity and wavelength

Nonlinear optical properties of chalcogenide glasses are very dependent on wavelength. We thus propose to perform a nonlinear characterization of Ge-Sb-Se on a wide wavelength range. Few results have been recently published for this material [8, 9]. These literatures have well characterized the nonlinear properties of chalcogenide glasses at shorter wavelength[8] (1030 nm) and mid-infrared[9] wavelengths (2000 nm and 2500 nm) by Z-scan technique. Since the studies are on a fixed wavelength, a step by step wavelength varying study is necessary to understand the influence of wavelength on the propagation of self-trapped beam. In this section, we report the optical characterization of the waveguide $Ge_{28.3}$-$Sb_{6.8}$-Se_{64}, by tuning the wavelength from 1200 nm to 1570nm. Input beam width is similar than in the previous experiment from figure 2a. Output beam profile of best self-focusing behavior (strongly focused central beam) for different wavelength and its influence on power is depicted in figure 4. We note that self-focusing is observed for all tuned wavelengths. However, an almost clean or distinguishable beam size of self-trapped beam is formed at 1550 nm and 1200 nm. Besides, a similar width at the exit face and at the entrance face (soliton formation) is observed at 1550 nm. For all studied wavelengths, self-trapped beam is accompanied with the local maximum on each side. This is more dominant at shorter wavelengths. The strong Kerr coefficient in chalcogenide gives focusing in our experiment, but the contribution of absorption (2PA & 3PA) opposes the focusing and brings out wings on both sides of the beam. Also, we note that, the energy required for self-focusing is lower at shorter wavelength than the longer wavelength. For longer wavelengths the focusing is given by weak nonlinear coefficients and three photon absorption[10]. Self-trapped beam quality (soliton like behavior) couldn't improve by increasing the input power. If we increase the power above the self-focusing threshold, the wings become more intense and lead to beam splitting. The clean self-trapped beam at 1550 nm and 1200 nm could be easier compared to simulations and to extract the Kerr coefficient. We found $n_2 = 3.4 \times 10^{-18}$ m^2/W for the wavelength of 1200 nm and found a good agreement with literature value measured by Z-scan[8]. The n_2 value for 1550 nm is mentioned in the first section. The high optical nonlinearity measured at shorter wavelength is interesting for photonic applications.

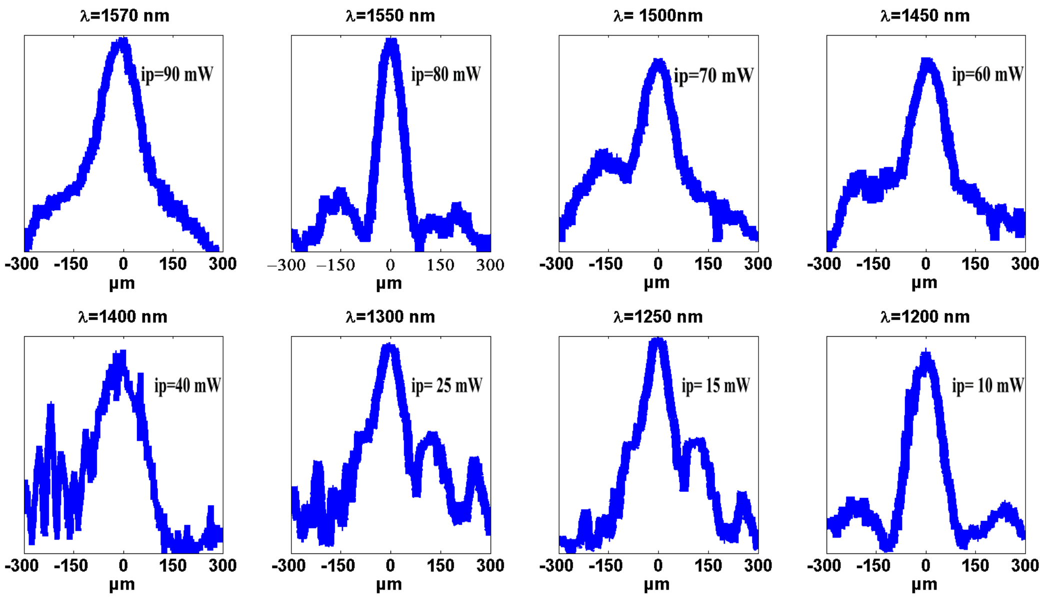

Figure4. Experimental output beam profiles of the best self-focusing behavior obtained as a function of wavelength in the $Ge_{28.3}$-$Sb_{6.8}$-Se_{64} waveguide.

Photo-induced self-trapping of optical beam

In addition to the instantaneous nonlinear Kerr response presented before, we have observed a slow and irreversible self-trapping of the optical beam when the illumination is maintained for a long time. We call this effect a photo-induced change. This refractive index variation under illumination has been studied for several decades and have been applied to the fabrication of devices such as gratings and waveguides[10] notably in of chalcogenide glasses .This photo-induced effects can come from different mechanism such as photo-crystallization, photo-polymerization, that lead to photo-compaction or expansion, photo-darkening and photo-bleaching[10, 11]. The effects induce changes in the optical constants such as the refractive index, the absorption coefficients and the optical band gap[10]. Photo-induced phenomena are stronger when illumination is performed a wavelength near the optical band gap of the material. Also, the photo induced modification of refractive index takes place slower at lower laser power. In this section, we discuss the photo induced beam self-trapping and photosensitivity studies in both $Ge_{28.3}$-$Sb_{6.8}$-Se_{64} and $Ge_{12.1}$ $Sb_{25.5}$ $Se_{62.5}$ compositions.

In order to study this effect, the same experimental setup as for the beam self-action is used. The measurements were carried out at 1.55 µm in femtosecond regime for an illumination time of about an hour. Evolution of the beam distribution at the output of the $Ge_{28.3}$-$Sb_{6.8}$-Se_{64} waveguide as a function of time is shown in figure 5, for an input power of 70mW. At the beginning of light exposure, the input beam of 42 µm (FWHM) diffracts to 110 µm through the 1.2 cm long waveguide (fig 5a). Then the beam tends to reshape gradually to form weak peaks on each side of the central beam that tends to enlarges as seen in fig 5b-5c). As time evolves, multiple peaks formation is observed (fig 5d-5f). At t=1380 s, the lateral peaks are as intense as the central peak, as observed at t=2040s (fig 5e). At the end of photo induced process the beam start to splits asymmetrically due to the strong photo induced absorption. Photo-induced absorption and scattering are known to be present in chalcogenide on exposure to high power irradiation, when the photon energy is less than the band gap[10]. Hence, photo-induced losses (absorption) are present in this composition with an irradiation of low energy photon (0.8eV) than the material bandgap (2.16 eV). Waveguide $Ge_{28.3}$-$Sb_{6.8}$-Se_{64} is thus highly photosensitive at 1.55µm under high illumination intensity. It gives rise to a strong beam dislocation.

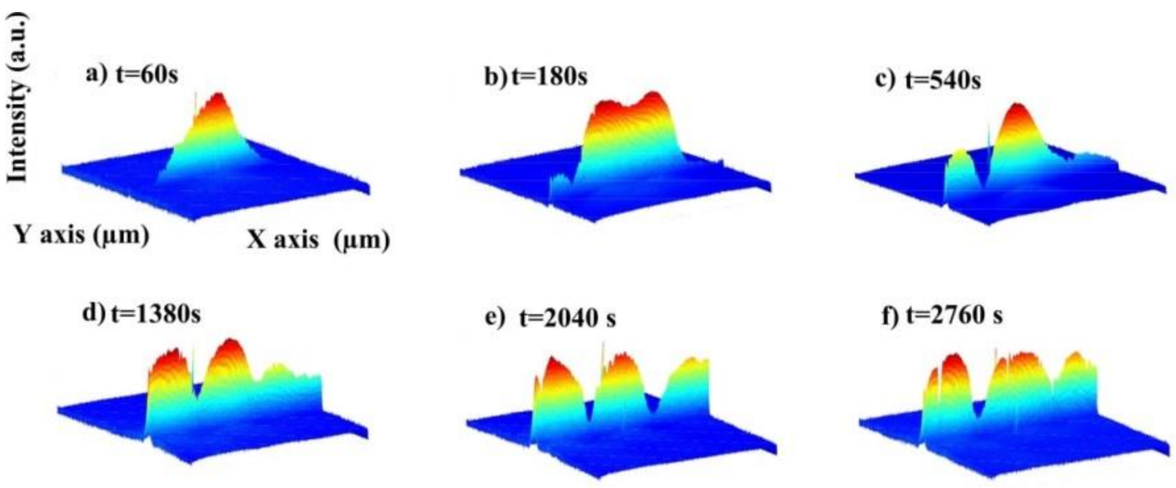

Figure 5: Evolution of beam size with time for intensities of about 0.78 GW/cm^2 ($Ge_{28.3}$ $Sb_{6.8}$ $Se_{64.9}$).Profile of 110 µm wide output beam at t=60 s (a). Temporal evolution leads to multiple peak formation (c-f).

Similar experiments are done in $Ge_{12.1}$ $Sb_{25.5}$ $Se_{62.5}$ that has bandgap energy of 1.7eV. Experimental results on the evolution of output beam size with time in the nonlinear regime of propagation are shown in figure 6 for an illumination intensity of 1.4 GW/cm^2. At first, the 42 µm input beam width (Fig.6a) experience free diffraction to 118 µm (fig.6b).Then the beam starts to focus gradually, it is shown in fig 6b-6f. At the end of photo-induced process, the output beam is clearly focused (42µm, fig.6f) and has a width similar than the input beam. The self -trapped beam maintain its shape for about 14 minutes. Since the process continues to evolve the beam width becomes smaller (32µm) than the input beam. In other terms, diffraction is balanced by the photo induced index change. Similarity of the input (fig.6a) and output beam (fig. 6f) profiles is an indication of soliton formation by the photo- induced effect. These effects thus give an increase of the index of refraction in the illuminated area[10]. If we stop the illumination a guiding structure is present. After comparing the results in both compositions, we found that studied compositions are photosensitive and the observed effects are irreversible because when the intensity is lowered, the diffraction regime is not recovered like when the Kerr effect is dominant. The highest damage threshold intensity is found for $Ge_{12.1}$ $Sb_{25.5}$ $Se_{62.5}$ guiding layer.

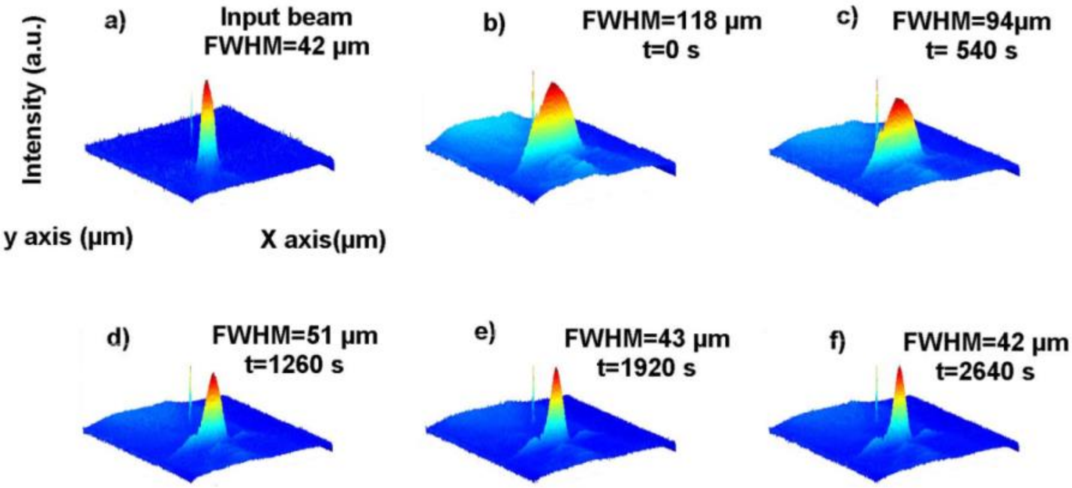

Figure 6: Evolution of the optical beam distribution at the output of the $Ge_{12.1}$ $Sb_{25.5}$ $Se_{62.}5$ waveguide for an input intensity of about 1.4GW/cm$^{2.}$ (b- f) a) Profile of the input beam.

In conclusion, we have demonstrated that beam profile analysis due to the self-action beam is an adequate technique to measure the optical nonlinearity in planar waveguides. The technique is used to analyze the Kerr effect along with the photosensitivity of chalcogenide Ge-Sb-Se slab waveguides. The found nonlinear refractive index coefficients are consistent with values obtained by z-scan technique. Optical nonlinearity as a function of wavelength is also presented. In addition, we report the experimental observation of an efficient beam self-trapping and soliton-like behavior in one chalcogenide waveguide due to a photo-induced effect.

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