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Mathieu Chauvet,[1,*] Gil Fanjoux,[1] Kien Phan Huy,[1] Virginie Nazabal,[2] Frédéric Charpentier,[2] Thierry Billeton,[3] Georges Boudebs,[4] Michel Cathelinaud,[5] and Simon-Pierre Gorza[6]

[1]*FEMTO-ST, CNRS UMR 6174, Université de Franche-Comté, 16 Route de Gray, 25000 Besançon, France*
[2]*Sciences Chimiques de Rennes, CNRS UMR 6226, Université de Rennes I, Campus de Beaulieu, 35042 Rennes, France*
[3]*Laboratoire de Physique des Lasers, CNRS UMR 7538, Université Paris XIII, 99 Avenue Jean-Baptiste Clément, 93430 Villetaneuse, France*
[4]*Laboratoire POMA, FRE 2988, Université d'Angers, 2 Boulevard Lavoisier, 49045 Angers, France*
[5]*Institut Fresnel, CNRS UMR 6133, 13397 Marseille, MRCT UPS2274, 92190 Meudon, France*
[6]*Service OPERA-Photonique, Université Libre de Bruxelles (ULB), 50 F. D. Roosevelt CP 194/5, 1050 Bruxelles, Belgium*
**Corresponding author: mathieu.chauvet@univ-fcomte.fr*

Kerr spatial solitons are observed in slab chalcogenide waveguides at near-IR wavelengths. Waveguides are realized either by electron-beam evaporation or rf sputtering of a Ge–Sb–S compound deposited on oxidized silicon wafer. The Kerr coefficient of the thin film is evaluated to be 5×10^{-18} m^2/W from the experimentally required soliton power at 1.5 μm. Limitations due to material photosensitivity are revealed.

Optical spatial solitons are shape-invariant self-guided beams of light that propagate in nonlinear media thanks to a dynamical balance between diffraction and a self-focusing effect. They were first theoretically described in the early 1960s [1], and a few years later, with the advent of laser sources, the first experimental observations of these self-trapped beams were reported [2]. Since then, owing to their promising applications for all-optical signal processing, they have been extensively studied both theoretically and experimentally [3]. A large variety of nonlinear media can support soliton propagation [4–6], but the search for nonlinear media having large ultrafast optical nonlinearities as well as a good nonlinear figure of merit is still relevant. Among promising Kerr materials are chalcogenide glasses, which possess large optical nonlinearities in the infrared spectrum [7] and are relatively easy to process. Nowadays, these materials are therefore subject to an intensive research in order to use them for realizing optical devices such as integrated optics components [8] or fiber lasers [9]. However, to date no experiment has been reported on beam self-trapping by Kerr nonlinearity in thin films made up of chalcogenide glasses, though this is of particular importance for potential applications.

In this work we report on experiments on self-trapped beams in Ge–Sb–S-based chalcogenide waveguides in the near-IR spectral region. The good quality of our planar waveguides allows us to observe the propagation of spatial bright solitons, asserting a positive Kerr nonlinearity at these wavelengths. We observed, however, that on a longer time scale the photosensitivity of our chalcogenide compound leads to a progressive degradation of the Kerr self-guiding properties.

Ge–Sb–S-based chalcogenide glasses are chosen because of their good transparency properties in the $\lambda=0.6$ μm to $\lambda=11$ μm spectral range, their strong nonlinear properties, and their moderate glass transition temperatures (200–400°C) strengthened by the presence of fourfold coordinated germanium, which increases the cross linkage of the glass network [10]. The glasses were prepared by means of conventional melting and quenching in order to obtain targets with versatile compositions for film deposition. The glass target purity is enhanced by specific purification process [11]. Two glass composition targets are thus obtained with different Sb/Ge ratios, $Ge_{15}Sb_{20}S_{65}$ ($T_g=250$°C) and $Ge_{25}Sb_{10}S_{65}$ ($T_g=355$°C). The nonlinear optical properties of these glasses were characterized by a standard Z-scan technique at a wavelength of 1.06 μm with bulk samples using CS_2 as a reference to calibrate the setup. The Kerr nonlinear coefficients were measured to be $n_2=4.5\times10^{-18}$ m^2/W and 3.1×10^{-18} m^2/W for $Ge_{15}Sb_{20}S_{65}$ and $Ge_{25}Sb_{10}S_{65}$ compositions, respectively. The two-photon absorption coefficient was found to be lower than the sensitivity of our Z-scan apparatus (0.05 cm/GW) for the $Ge_{15}Sb_{20}S_{65}$ sample, while a value of 0.2 cm/GW was estimated for the $Ge_{25}Sb_{10}S_{65}$ composition.

The slab waveguide structures were made by deposition of thin chalcogenide films onto 1 or 2 in. diameter oxidized silicon wafers [11]. Two deposition techniques were implemented, rf sputtering and electron-beam deposition (EBD). Both methods give structural organization and chemical composition of the films very close to bulk glass target as confirmed by Raman scattering analysis and energy dispersive spectroscopy measurements [10]. Film thickness and refractive index were characterized by scanning electron microscopy, M lines, spectrophotometry, and ellipsometry. Two slab waveguides were realized, one with a 3-μm-thick $Ge_{25}Sb_{10}S_{65}$ guiding layer deposited by the rf sputtering technique and the other with a 5-μm-thick guiding layer of $Ge_{15}Sb_{20}S_{65}$ deposited

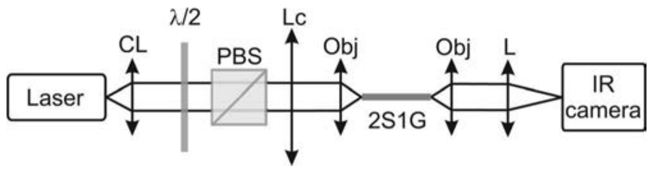

Fig. 1. Experimental setup for the study of bright Kerr solitons in slab chalcogenide waveguides. CL, collimating lens; λ/2, half-wave plate; PBS, polarizing beam splitter; L_c, cylindrical lens; Obj, microscope objective; 2S1G, slab waveguide; L, lens. The laser source is either a 1.06 μm Nd:YAG, 700 ps pulse duration microchip laser or a 1.53 μm, 5 ps amplified fiber laser.

by EBD. Samples were then cleaved to allow standard butt coupling at the waveguide input along with direct imaging at the output. Propagation losses were measured to be less than 1 dB/cm at a 1.5 μm wavelength, showing excellent linear optical properties. Since the chalcogenide refractive index was measured to be near $n=2.4$ at $\lambda=1.5$ μm, as many as 10 modes are expected to be guided in the waveguide structure, requiring special care when injecting light into the waveguide in order to excite only its fundamental mode.

The typical experimental setup is shown in Fig. 1. The laser beam is first collimated, then shaped and coupled into the 1-cm-long waveguide by means of a cylindrical lens and a microscope objective. A half-waveplate and a polarizing beam splitter allow us to continuously change the input power. The input laser beam width in the guided direction [3 or 5 μm (FWHM) depending on the actual waveguide] is chosen to efficiently excite the fundamental TE mode of the waveguide. At the waveguide output, the beam is imaged onto a camera by a second microscope objective. In the transverse dimension, the input beam width is set to 45 μm (FWHM), which corresponds to a soliton peak intensity of approximately 2 GW/cm^2 [3], assuming that nonlinear properties of thin films are identical to bulk chalcogenide glasses.

The first experiment was performed at a wavelength of $\lambda=1.53$ μm in the 3-μm-thick slab waveguide of $Ge_{25}Sb_{10}S_{65}$. The laser source is a picosecond fiber laser delivering 5 ps pulses at a 10 Mhz repetition rate, amplified in a 23 dBm erbium-doped fiber amplifier. At low power, the 45 μm wide input beam broadens up to 95 μm because of diffraction experienced in the 1-cm-long sample (see left-hand column of Fig. 2). As can be seen, the high homogeneity of the chalcogenide film and the absence of any defects result in a good output beam quality. Moreover, on the basis of the intensity profile along the guided direction (y axis in Fig. 2), we verified that only the fundamental mode of the slab waveguide is excited. As depicted in Figs. 2(c) and 2(g), at an average output power of 50 mW, the beam clearly self-focuses to reach the input beam width. The close match between the input and the output beam profiles leaves no doubts about the formation of a spatial soliton. When light power is lowered, the diffraction regime is recovered accordingly with a Kerr process. From the power level required to observe the fundamental soliton, the nonlinear Kerr coefficient (n_2) of the chalcogenide film can be evaluated. Indeed, from the theory of soliton formation in a nonlinear planar waveguide, this coefficient is linked to the soliton power P through the expression $n_2=\lambda h_{\text{eff}}/[\pi\beta x_0 P]$, where h_{eff} is the effective fundamental mode width, β is the guided mode wavenumber, and $\Delta x(\text{FWHM}) =2\ln(1+\sqrt{2})x_0$ is the soliton width assuming a hyperbolic secant beam profile. The 45 μm beam width therefore leads to a coefficient of the order of $n_2=5\times10^{-18}$ m^2/W, in fair agreement with the value obtained from Z-scan measurements at a wavelength of $\lambda=1.06$ μm.

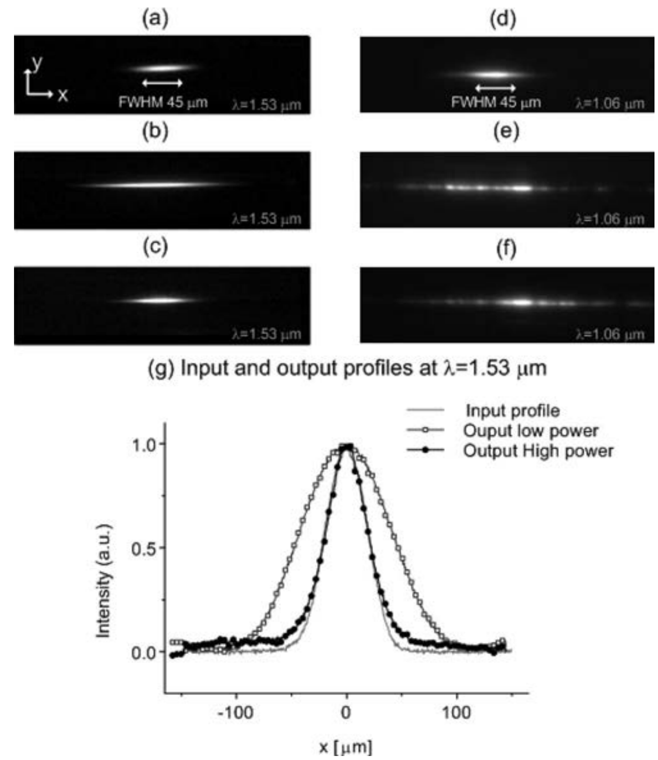

Fig. 2. Experimental results showing both soliton beam formation and self-focusing at (a), (b), (c) $\lambda=1.53$ μm and (d), (e), (f) $\lambda=1.06$ μm in $Ge_{25}Sb_{10}S_{65}$ and $Ge_{15}Sb_{20}S_{65}$ chalcogenide slab waveguides, respectively. (a), (d) Laser beam profile at the input of the guiding structure. (b), (e) Output beam profile at low power and (c), (f) in the nonlinear regime of propagation at a peak intensity of 1 GW/cm^2. (g) Intensity profiles corresponding to Figs (a)–(c).

Additional single-shot experiments were realized with a laser source delivering a 700 ps pulse duration at a wavelength of $\lambda=1.06$ μm. The sample used in this experiment is the 5-μm-thick slab waveguide deposited by EBD ($Ge_{15}Sb_{20}S_{65}$). Unlike in the previous sample, it was not possible to find a suitable location in the waveguide to experimentally observe soliton formation. Indeed, the diffracted output beam has an intensity profile far from a Gaussian shape, as can be seen in the right-hand column of Fig. 2, where typical experimental results are reported. Consequently, at high intensity, even though a self-focusing effect is clearly observed [see Fig. 2(f)], the output beam does not reach the input beam profile. A nonlinearity response time shorter than 700 ps can be inferred from this single-pulse self-trapping observation. The re-

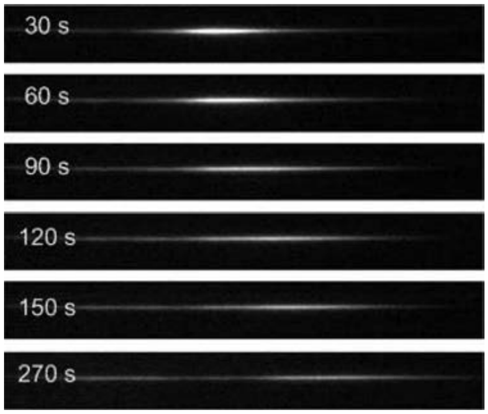

Fig. 3. Slow temporal evolution of the output beam in the nonlinear regime of propagation. These results were obtained at $\lambda=1.53$ μm. At $t=0$ s (not shown), the output beam profile matches the input beam as in Figs. 2(a), 2(c), and 2(g).

sults thus confirm the presence of a fast Kerr effect and preclude the influence of material photosensitivity.

Beside the observation of spatial solitons, we have studied how the glass photosensitivity can affect the evolution of self-focused laser beams for long illumination times. It is indeed well known that chalcogenide glasses are photosensitive, especially at visible wavelenghts [7]. Light-induced permanent index change at IR wavelengths, i.e., in the transparent spectral region, has also been reported and was attributed to multiphoton absorption [12,13]. Such a photosensitivity could severely limit the suitability of chalcogenide glasses for applications [8,9] or, on the contrary, could be used to induce index changes inside bulk glasses [14]. In our samples photosensitivity already affects the beam propagation after few pulses at $\lambda=1.06$ μm. At the 1.53 μm wavelength the photosensitivity is also present despite the fact that the photon energy is less than a third of the material bandgap (2.48 eV). From the initial soliton regime, photosensitivity is revealed by the broadening of the output intensity profile depicted in Fig. 3. Soliton perturbation becomes significant after more than 1 min exposure time. Note that for the glass compositions used the influence of the Kerr effect and photosensitititivity can be easily dissociated, since they induce fast focusing and slow defocusing effects, respectively. The photosensitivity first tends to broaden the output beam, then to split it, in such a way that a low-intensity region appears where the maximum of the soliton intensity was previously located. In Ge–Sb–S compounds, the photosensitivity at near-IR wavelengths thus induces an antiguiding structure, contrary to what is observed in the commonly used As_2S_3 chalcogenide glass [12,13].

In conclusion, we report on the experimental observation of spatial Kerr solitons in amorphous-chalcogenide planar waveguides at near-IR wavelengths. The waveguides are composed of Ge–Sb–S based thin film deposited on oxydized silicon substrate. By propagating a soliton beam in these waveguides we have shown that these thin glass films possess good optical quality as well high nonlinear properties together with low linear losses, making them potentially suitable for ultrafast optical nonlinear applications. However, severe limitations arise from the material photosensitivity that tends to slowly change the refractive index of the glass. Further investigations are currently being carried out to better understand and characterize this photosensitivity that occurs in the spectral transparent region of the chalcogenide compound.

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