Nonlinear effects generation in suspended core chalcogenide fibre

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ABSTRACT

In this work we report our achievements in the elaboration and optical characterizations of low-losses suspended core optical fibers elaborated from As_2S_3 glass. For preforms elaboration, alternatively to other processes like the stack and draw or extrusion, we use a process based on mechanical drilling. The drawing of these drilled performs into fibers allows reaching a suspended core geometry, in which a 2 μm diameter core is linked to the fiber clad region by three supporting struts. The different fibers that have been drawn show losses close to 0.9 dB/m at 1.55 μm. The suspended core waveguide geometry has also an efficient influence on the chromatic dispersion and allows its management. Indeed, the zero dispersion wavelength, which is around 5 μm in the bulk glass, is calculated to be shifted towards around 2μm in our suspended core fibers. In order to qualify their nonlinearity we have pumped them at 1.995 μm with the help of a fibered ns source. We have observed a strong non linear response with evidence of spontaneous Raman scattering and strong spectral broadening.

Keywords: fiber, nonlinear optics, chalcogenide glasses

1. INTRODUCTION

Microstructured optical fibres (MOFs) came up during the 90's [1], since then this new class of fibre have led to huge research effort all over the world due to its innovative properties compared to the traditional standard fibers. Many applications in different fields are associated with these fibres, obviously in telecommunication but also in biology or metrology among others [2-4], most of them being based on silica glass. Hence, most of these applications are limited to the visible and near infrared while interests exist further in the infrared such as light amplification, optical regeneration, sensing and supercontinuum generation [5-8].
It is well know that chalcogenide glasses exhibit high transparency in the mid-IR region (10-20 μm) together with high refractive index (n = 2.0 - 3.5) and high non linearity [9]. Consequently, this class of materials gathers good candidates for applications, and particularly for nonlinear optics, in this spectral range [9, 10]. In addition, the design of microstructured optical fibers is a way to both increase the nonlinearity of the waveguide and control its losses and chromatic dispersion [11-13] [18–20]. The latter parameter is a key tool to obtain an efficient light conversion and to reach accordable fibered broadband sources in the mid infrared.

Optical Sensors 2011; and Photonic Crystal Fibers V, edited by Francesco Baldini, Jiri Homola, Robert A. Lieberman, Kyriacos Kalli, Proc. of SPIE Vol. 8073, 80732H · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.886720

Much effort has been recently devoted to obtain MOFs from various glasses and different fabrication processes have been used as stack and draw or extrusion [14-18]. Here we propose an alternative way of preform elaboration: mechanical machining. By this way we obtained suspended core fibre with core diameter around 2 µm, in which we succeeded to generate non linear effects.
Firstly we describe the glass fabrication, then the perform preparation, the fibre drawing and the optical characterizations. Finally, in order to qualify their non linearity we have pumped them at 1.995 µm, close to their zero dispersion wavelength, with the help of a fibered ns source.

2. PREPARATION OF AS_2S_3 GLASS AND MICROSTRUCTURED FIBRES (MOF).

Among the numerous chalcogenide glasses, we have chosen the arsenic trisulphide (As2S3) glass. Indeed, this glass shows high non linear properties. The non linear refractive index n_2 is measured between 3 and 5.10^{-18} m²/W depending on the wavelength [19-20]. This composition shows also a high drawing capability and potential very low losses [21]. It is also transparent from the end of visible up to 6 µm in a fiber geometry.
The required amounts of the different elements (S and As) are placed in a silica ampoule under vacuum (10^{-5} mbar). In order to purify starting elements from their remaining pollutants such as water or carbon, the sulfur is purified using dehydration and distillation procedures while the arsenic oxides are vaporized by sublimation process [22]. After sealing, the ampoule is introduced in a rocking furnace and progressively heated up to 700 °C. The ampoule is maintained at this temperature for 12 h, before being quenched in water to allow glass formation and avoid any crystallization process. The vitreous sample is then annealed for several hours at the glass temperature (Tg = 210 °C) to relax the internal mechanical stress induced by quenching, and it is slowly cooled to room temperature. A glass rod is subsequently obtained. The glass rod is typically 7 cm length for 16 mm diameter.
The usual technique to prepare microstructured perform is stack and draw but this process presents several disadvantages. It consists in staking capillaries and rods, thus forming on a macroscopic scale, the desired fiber microscopic geometry. However, because multiple stages of the elaboration are necessary it is time consuming. Handy manipulation causes surfaces degradation and there is the presence of interstitial holes. These features generate higher optical losses [23]. To overcome these problems and to avoid the multiple steps imposed by the stack and draw procedure, we have chosen an alternative technique. After annealing, the glass rod undergoes mechanical machining to get three holes of typically 1 mm diameter and 40 mm length around a solid core. The preforms prepared this way are then drawn into fibers. By controlling the drawing parameters (temperature, pressure in the holes etc...) we obtain suspended core fiber, with various diameter cores around 2.5 µm (fig 1).

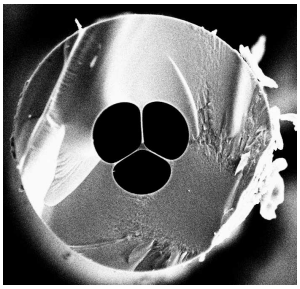

Figure 1: SEM image of our As2S3 suspended core fibre with a core diameter of 2.6 µm

3. OPTICAL CHARACTERIZATION OF AS_2S_3 MOF

The material losses of the MOF are measured on a single index fiber of the same glass by the cutback method (fig. 2) [24]. For the fiber presented figure 1, the background level of losses of the corresponding single index fiber is around 1 dB/m between 2 and 6 µm. We observe an extrinsic S-H absorption band at 4 µm. This absorption corresponds to a residual pollution of the glass. The extinction coefficient associated to the SH vibration being 2.5 dB/m/ppm [25] at 4 µm, the residual SH content is of 9 ppm.

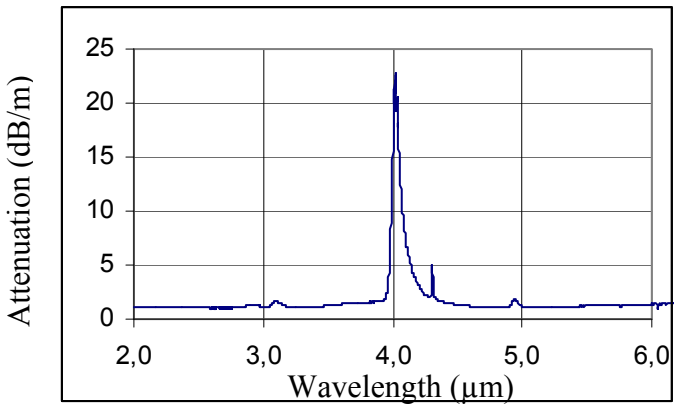

Figure 2: Spectral losses of the single index As_2S_3 fiber.

We have then measured the losses of the suspended core MOF. Due to the small core of this fiber, it was not possible to obtain the spectral attenuation curve using our FTIR spectrophotometer. We have then performed discrete measurements with the help of a fibered source at 1.55 µm. On 2 meters of the 2.6-µm core MOF, the losses are found to be around 0.9 dB/m. This is fully consistent with the attenuations obtained on single index fibers.

Our machining process allows obtaining microstructured fibers without any excess of losses due to the preform elaboration process, as it is generally observed with the stack and drawing procedure. Based on previous calculations [26], the zero dispersion wavelength (ZDW) is around 2.2 µm. Thus, we are able to fabricate chalcogenide suspended core fibre with adequate geometry and losses low enough to generate nonlinear effects. This will be the subject of the following sections.

4. EXPERIMENTATION

4.1 Experimental Set up

The 4.4 m long fiber is pumped with a 2 µm fiber laser as shown in Figure 3. This source is a "gain switched" thulium-doped fiber laser [27] with central wavelength at 1995 nm (2 nm full width at half maximum). The pulse duration is 20 ns. An isolator is used to prevent light reflections from the fiber cleave back to the laser. To improve the coupling efficiency with the chalcogenide fiber, a few centimeters of ultra high numerical aperture fiber (UHNA) are spliced after the isolator. The UHNA and the AsS fiber are butt-coupled using a splicer.

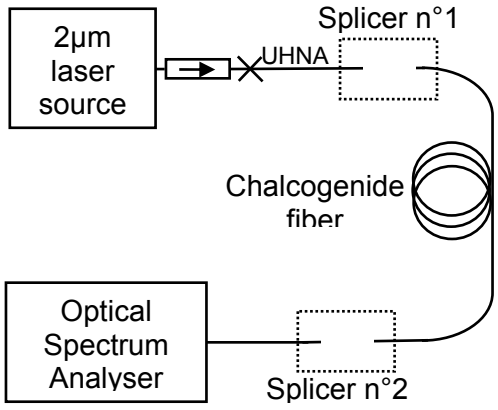

Figure 3: Experimental set-up for the fiber characterization

Light after the chalcogenide fiber is collected using a 200 µm diameter multimode fiber. This multimode fiber is connected into high resolution optical spectrum analyser up to 2400 nm.

4.2 Results

The coupling ratio corrected from the Fresnel reflections and the transmission of the fiber is evaluated to 43 %. Due to injection stability and uncertainty in coupling efficiency, the peak power is known within 20% error.

By varying the injected peak power of the nanosecond source we obtain spectra shown in Figure 4.

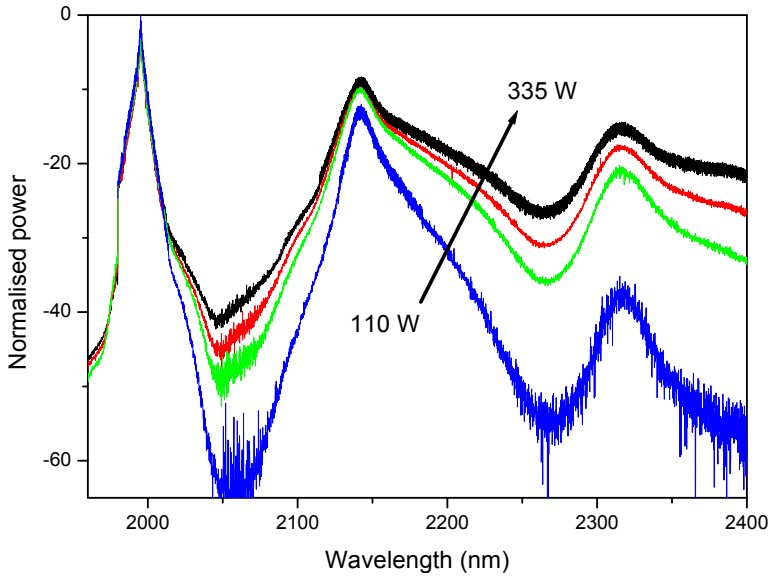

Figure 4: Output spectra for different injected peak power (110 W, 180 W, 300 W, 335 W) up to 2400 nm in a 4.3 m long fiber

At the output of the chalcogenide fiber, we observe 2 Raman shifts. The stokes orders appear respectively at 2140 and 2315 nm. Injection of 1995 nm nanosecond pulses into the As-S fibers in the normal dispersion regime leads to Raman scattering as modulation instability is prevented by dispersion and self-phase modulation is negligible for ns pulses. The zero dispersion wavelength of the fiber is located around 2,2 µm [26]. From this wavelength, the spectum begins to broaden for high peak power. The power spectral density is growing up between the two stokes orders (2260 nm) as we increase the injected peak power.

4.3 Raman gain measurement

For the raman gain measurement, we use the same set-up as shown in Figure 3 but with the 2 µm laser at lower peak power. We vary the power of the 2 µm source and obtain the curves in Figure 5.

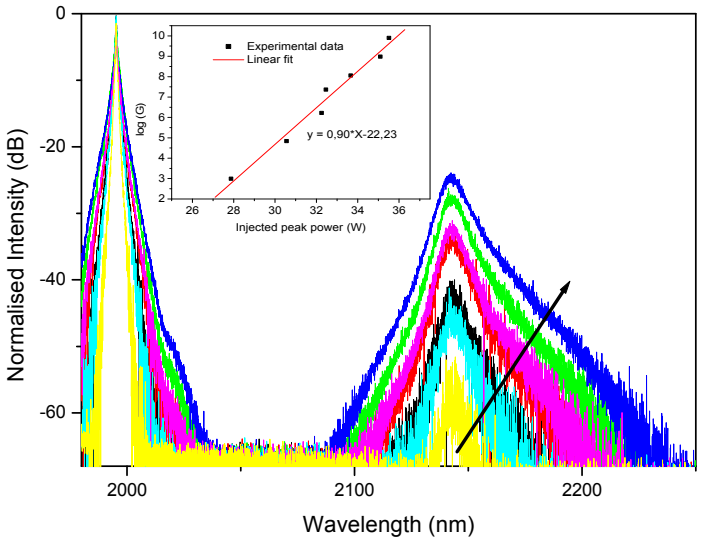

Figure 5: Evolution of the first Raman shift for increasing peak power from 50 W to 64 W. In the inset the total gain between the top of the first Raman shift and the noise floor at the same wavelength is plotted as a function of the injected peak power

A rough estimate of the Raman gain coefficient g_R is given by the following relation:

$$G_A = \exp\left(\frac{g_R P_0 L_{eff}}{A_{eff}}\right) \quad (1)$$

where G_A is the total Raman gain between the top of the first Raman shift and the noise floor at the same wavelength, P_0 is the injected peak power known at 20%, A_{eff} the effective mode area of the fiber (7,5 µm² for our fiber), and L_{eff} the effective length given by

$$L_{eff} = \frac{1}{\alpha}\left(1 - e^{-\alpha L}\right) \quad (2)$$

where α is the loss of the fiber and L the fiber length. The fiber is 4.3 m long and the attenuation is ~0.4 dB/m. This leads to an effective length of 3.6 m. We estimate a g_R of 1.8×10^{-12} m/W at 2 µm for the fiber which is ~360 times higher than in silica fiber for the same wavelength. Ref. [28] gives Raman gain coefficient of 4.4×10^{-12} m/W at 1.55 µm. Furthermore it is known that the Raman gain coefficient scales inversely with the pump wavelength [29]. For Ref. [28] we calculated g_R of and 3.3×10^{-12} m/W at 2 µm. Consequently, the value found for our fiber is in good agreement with the literature. A better estimate of the Raman gain coefficient could be computed using a dynamic modelling.

5. CONCLUSION

We have successfully demonstrated the elaboration of low-losses suspended core optical fibers from As_2S_3 glass. For the elaboration of the microstructured fiber we use an alternative process based on mechanical machining. We obtain a 2.6 µm diameter core suspended fiber with losses around 0.9 dB/m at 1.5 µm.
This fiber was pumped at 1.995 µm and we obtain strong spectral broadening. We observe 2 Raman orders at 2140 and 2315 nm. We also measure the Raman gain coefficient at 1.995 µm. We found $g_R = 1.8\times10^{-12}$ m/W witch is coherent with the litterature value.

For future work, we will work on AsSe fiber. Further reducing the core size we will shift the zero dispersion wavelength to shorter wavelengths.

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