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Microstructured Optical Fibers Made of Chalcogenide Glass for the Generation of Optical Functions

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Abstract This work reports on the fabrication and optical characterization of microstructured optical fibers (MOF) made of chalcogenide glass $A_{S2}S_3$. For the fabrication, the Stack and Draw method was used and for the characterization, a simulation software (OptiSystem) was also used. The results of this study are as follows: the refractive index of the microstructured chalcogenide glass fibre is $1.1.10^{-18}$ m^2/w much higher than that of standard silica fibre, which is 2.6 10^{-20} m^2/w. The non-linear refractive index of these chalcogenide fibers provided to be 100 times higher than that of the standard fiber. The characterization of the Brillouin and Raman diffusion effects also gave excellent results, with respective gain values of 8.10^{-10} $W^{-1}Km^{-1}$ and $1.8.10^{-10}$ $W^{-1}Km^{-1}$, thus validating an exacerbation of the non-linear effects within this type of fiber. These results were then used to generate optical functions.

Keywords: *optical functions, microstructured optical fibers, non-linear properties*

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1. Introduction

Since the appearance of Erbium-doped fiber optic amplifiers in the 1990s, transmission distances have taken a giant step forward [1]. An increased from around 200 km to more than 6,000 km in transoceanic applications is achieved. From then on, a dazzling race for a perpetual increase in the transmission rate was lunched. A great deal of work was carried out to determine the effects that could hamper signal transmission as the rate increases [2].

The measurement of chromatic dispersion by the interferometric method, the measurement of optical losses by the cut-back method and some experimental set-ups to determine phenomena that can be disturbing such as birefringence, the Raman and Brillouin effect, the effects of self phase modulation (SPM) and the non-linear kerr coefficient have been set up by some researchers [7].

This increase in the repetition rate irremediably implies a decrease in the width of the optical pulses, and an increase in peak powers, for the same energy. This increase in energy then gave rise to new phenomena such as higher order dispersions [3], problems related to time jitter [4], polarisation mode dispersion [5], or the exacerbation of non-linear effects [6].

However, the increase in throughput will be irremediably accompanied by a greater degradation of the signal due to light/material interactions within the transmission fiber [7]. This is why the development of optical functions adapted to very high throughput appears today to be essential for processing and improving the quality of the signal to be transmitted.

The development of chromatic dispersion compensation modules, the design of erbium-doped fibre amplifiers, amplification and signal shaping devices such as the Mamyshev regenerator, spatial diversity and Doppler compensation in underwater wideband communication have so far been used to improve signal quality [8,9].

The main objective of our research is to implement an As2S3 chalcogenide glass microstructured optical fiber for the generation of optical functions based on their non-linear properties.

2. Methodology

Microstructured optical fibers (MOF) are manufactured using a variety of different techniques such as drilling, extrusion or moulding and draw assembly. It is the latter technique that is the most widespread today. It consists of making a preform identical to the target geometry by stacking capillaries and/or circulor rods of millimetre size, which makes it easier to control the microstructure (Figure 1). The FOM are then designed in the same way as conventionnal fibers, by carrying out the fabrication of the preform. The wide variety of geometries than can be produced using this technique (Figure 2) has made it possible to adjust the guiding properties, sometime dramatically. These properties are mainly defined by the periodic spacing of the inclusions of high/low d diameter inclusions.

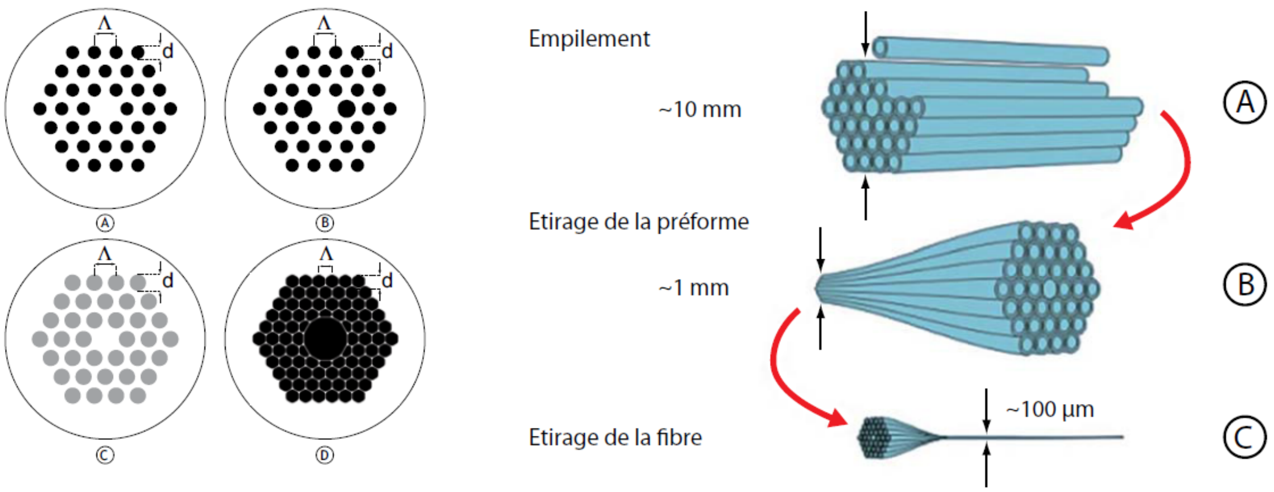

Figure 1. Schematic representations of different microstructured fibers structures. The black regions are air holes, the white regions are pure material and the grey regions are doped material. (a) High index core micfostructured fibers. (b) Polarisation maintaining microstructured fibers. (c) All solid fibers with band gaps and low index core. (d) band gap and hollow core fibers [10]

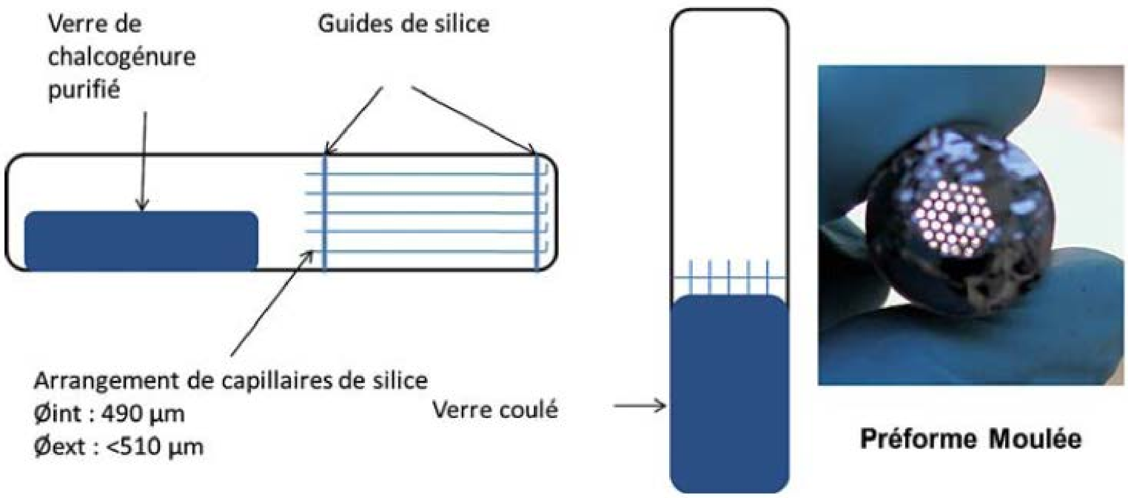

Figure 2. Diagram of chalcogenide glass preform manufacture using the moulding technique [10]

For the characterization we have used some methods to be known:

Optical loss measurement:

Knowledge of the value of optical losses during propagation is of crucial importance when working with non-linear phenomena. Losses can considerably reduce the length of interaction, thus limiting the application considered.

The cut-back method is very often used to measure the total attenuation an of optical fiber. It consists of cutting a part of the optical fiber that you wish to characterise and then making measurements (of power for example) according to the remaining length, and this is repeated for various lengths of the fibre to be tested. The cut-back method offers good measurement accuracy and resolution, however, the quality of the fiber cleavage and bundle injection must be regorous during the measurement process. Its use is typically limited to research and development and quality control laboratories. It is a destructive method as part of the optical fiber sample to be tested will be broken. This method will determine the optical attenuation in dB/m in a fiber system.

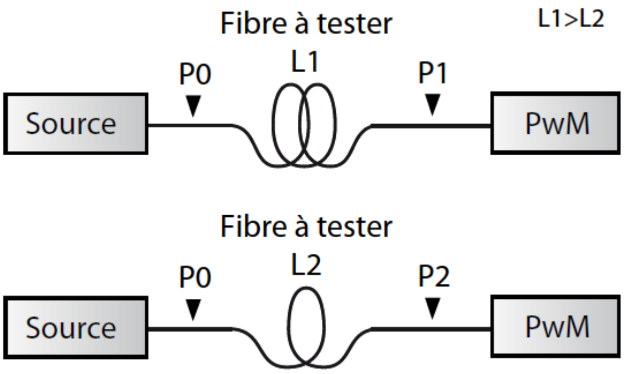

Figure 3. Principle of the cut-back method: powers are in dBm and lengths in metres

The measuring technique is as follows:

This explanation is based on Figure 3.

-Measure the power output of the fiber to be tested : P1 in (dBm)

-Cut a section in of the fiber to be tested (a few metres) without modifying the initial injection.

-Repeat the measurements on the short remaining length : measure the output power : P2 (dBm) hence the name Cut-back.

- The result is then determined using equation 1.

α represents the losses in dB/km with ΔL the difference in length between the initial and final section (L2-L1).

$$\alpha_{dB} = \frac{-10\log\left(\frac{P1}{P2}\right)}{\Delta L}\left(dB/km\right) \quad (1)$$

Chromatic dispersion measurement:

One of the most important properties, when a study or application is based on optical fibers, is of course chromatic dispersion. This also true when the design is based on semiconductors.

Various methods for measuring chromatic dispersion have been the subject of much work at the international level. Chromatic dispersion measurements in optical fibers are based on a variety of techniques, two of the main ones being : the first is interferometric measurement in short samples (a few centimetres) and the second is time-of-flight measurement in a long sample (several metres to several kilometres). Both methods provide reliable and accurate measurement of chromatic dispersion, and are used in the characterization of commercial and laboratory systems.

Figure 4.a shows the schematic diagram of the experimental setup for the characterisation of different optical fibers. A photograph of the experimental setup can be seen in Figure 4.b. The setup is based on a Mach-zehnder interferometer designed mainly with fiber components, which makes it easier to align compared to an open-air system.

This is made up of two arms : one arm commonly known as the reference arm in which a standard SMF-28 optical fiber (whose characteristics are perfectly known) is connected on one side to a 50 :50 coupler and on the other to a delay coupler. The latter will compensate for the optical path difference between the two arms as well as the delay caused by the difference in group speed. An interference pattern will thus be obtained by obtaining this equilibrium, can be seen in the diagram in Figure 4.

The second arm, known as the test arm, comprises the fiber to be tested, placed on an open air injection plate (adapted to a short sample, micrometric precision), connected to a standard SMF-28 fiber (associated with a micro-lens facilitating injection into the sample to be characterised), enabling the two arms to be balanced in terms of linear losses and optical lengths.

At the end of the assembly, the interference pattern is analysed by an optical spectrum analyser.

In order to measure a wide range of dispersion values with a reasonable accuracy of less than 5 ps/km.nm, a broadband source based on the generation of a supercontinuum ranging from 1100 nm to 1700 nm (measurement limited by the resolution of the optical spectrum analyser used) visible Figure 4 was used in the setup. The supercontinuum of this source is obtained by the non-linear amplification and propagation of a pulse train with a temporel width of 10 ps within a 500 m long Highly Non-Linear Fiber (HNLF). The pulse train is delivered by a 22 MHz mode blocking source (pritel source) centred around 1553 nm amplified to 28 dBm by an erbium-doped fiber ampliflier and then injected in to the HNLF. This highly non-linear fiber has the following characteristics : linear losses of 0.7 dB/km, an anormal dispersion of 0.56 ps/km.nm, a non-linear coefficient of 10.5 $W^{-1}Km^{-1}$ and a third order dispersion of 0.1ps/km.nm^2.

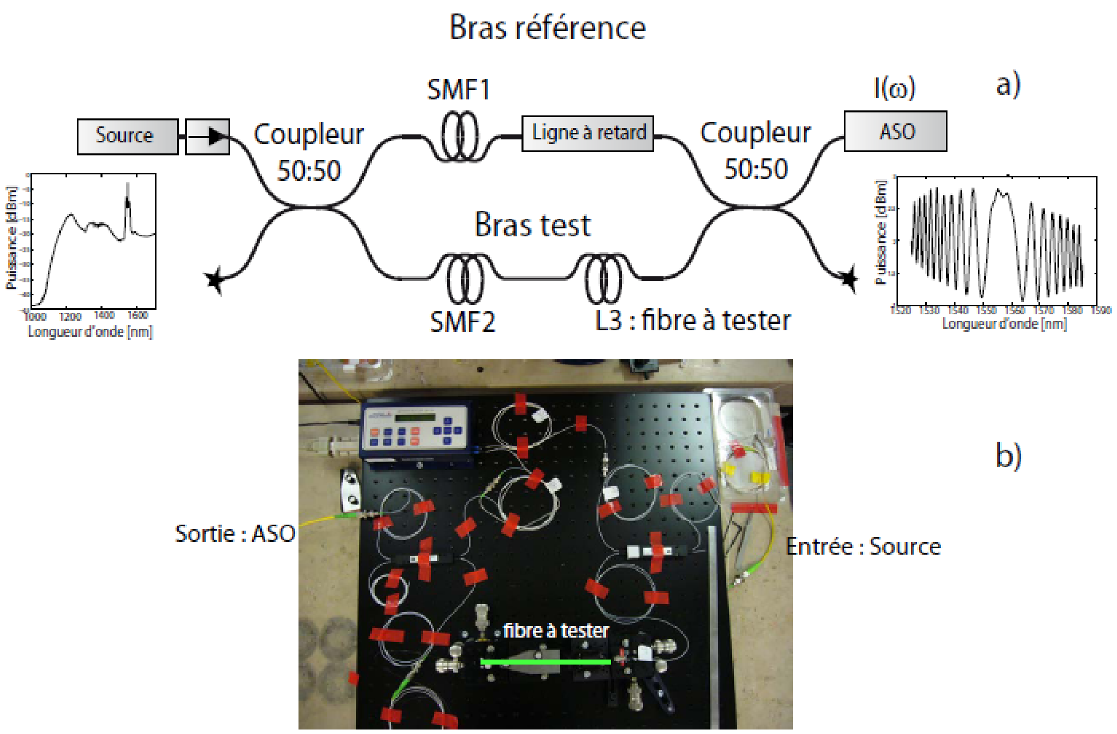

Figure 4. Principle of dispersion measurement by interferometric method: a) experimental scheme b) photo of the experimental bench

NB : attenuators have been placed within the reference arm to compensate for the losses introduced by the open air injection assembly. More than 50% of the injection losses and about 20% more are due to Fresnel reflection from the chalcogenide fibers tested.

Measurement of birefringerence

Accurate knowledge of the birefringerence within a fiber system is important when the system is dedicated to optical telecommunications or signal processing because it can induce a significant distortion of the information leading to a widening of the impulses as well as their deformation during their propagation within the optical fiber.

Birefringence is measured using the setup shown. By analysing the optical spectra obtained at the output, it is possible to determine the value of the birefringence.

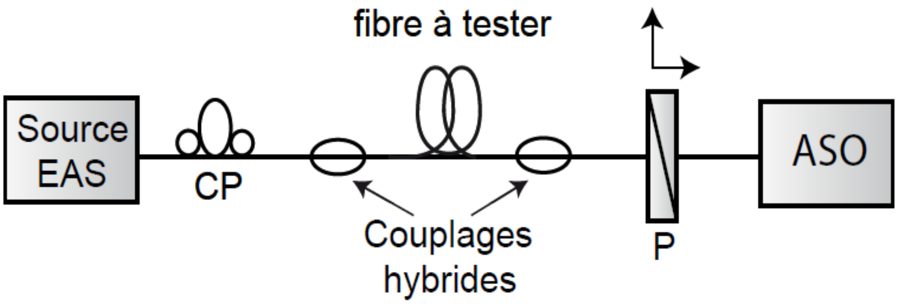

Figure 5. Experimental bench of the fluted spectrum measurement for birefringerence measurement

The experimental setup consists of a wide spectrum source with amplified spontaneous emission arround 1550 nm connected to a polarisation controller (CP). The optical signal is injected into the fiber to be tested by means of a mechanical welder facilitating alignment and signal injection during the characterisation of special microstructured optical fibers. At the output of the fiber, the field components along the slow and fast axes of the signal interfere on a polariser (P) before being detected by an optical spectrum analyser.

This technique allows the visualisation of a fluted spectrum. There is no direct measurement of birefringence but of the difference in group delay (DGD).

3. Résultats et Discussions

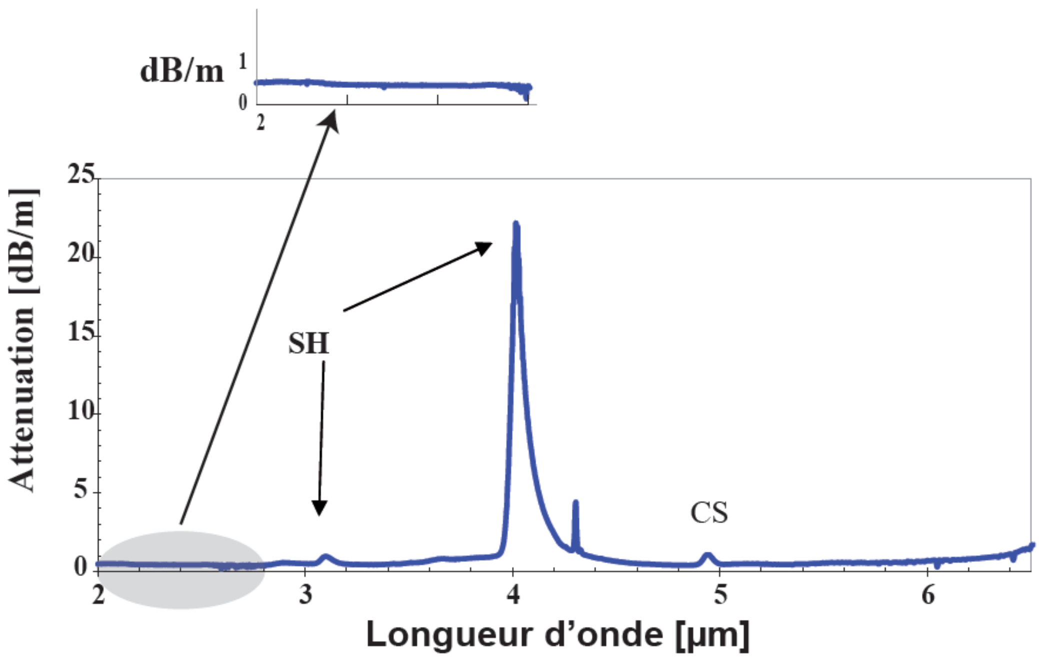

Figure 6. Attenuation diagram of a microstructured chalcogenide fiber As_2S_3

The diagram shown in the figure represents an attenuation measurement of a single index $\mathbf{As_2S_3}$ fiber with a diameter of 200 μm [1] made through the use of a Bruker Vector Spectrometer.

This characterisation reveals an extremely weak continuous background, which is favourable to the propagation of light over the corresponding wavelength range. The presence of absorption bands (SH, CS ions) is a sign of residual impurities. This simple diagram shows one of the main advantages of this type of fiber, the ability to work over a very wide range of wavelengths.

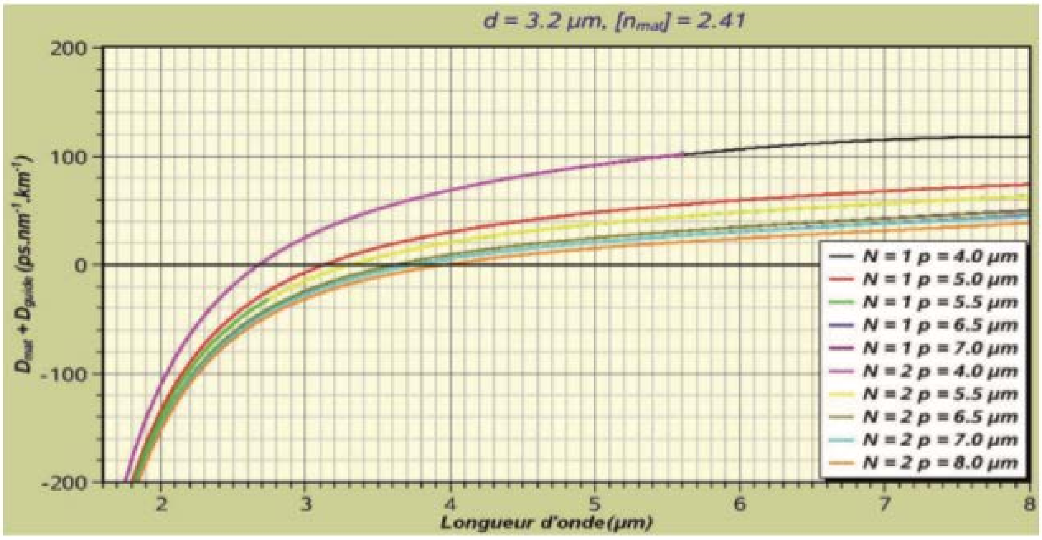

Figure 7. Graph resulting from the modelling of the evolution of the chromatic dispersion of a microstructured chalcogenide fiber As_2S_3 for a hole diameter set at d_n of 3.2 µm. N represents the number of hole crowns and p the intertitiel pitch

The evolution of the chromatic dispersion of a microstructured As_2S_3 fiber with a hole diameter of d_n de 3.2 µm is shown here. The modelling focuses on the modification of the parameters N representing the number of hole crowns, and p the intertitiel pitch. A clear change in the evolution of the chromatic dispersion curve can be seen by modifying these parameters.

Table 1. Characteristics of optical fibers. NC (Not Characterised)

Caractéristique	$GeSbS_1$	$GeSbS_2$	As_2S_3	SMF28
α(dB/m)	5	5,5	1,1	0,25 10^{-3}
A_{eff}(µm^2)	22	50	5,3	80
Biréfringence (ps/m)	5,5	0,8	NC	< 0,5
B_m	1,6 10^{-3}	2,4 10^{-4}	NC	< 10^{-4}
D (ps/nm/km)	-421	-406	-280	17
S(ps/nm^2/km)	0,9	1,1	1	0,07
$\gamma(W^{-1}\,Km^{-1})$	500	210	2100	1,3 m^{-1}
n_2 (m^2/W)	2,8 10^{-18}	2,6 10^{-18}	1,1 10^{-18}	2,6 10^{-20}
$\Delta\vartheta B(GHz)$	NC	-8,5	NC	-11
gB(W^{-1} Km^{-1})	NC	8 10^{-10}	NC	8 10^{-12}
P_{th}(mW)	NC	1950	NC	50
FOM (dB/mW/m)	NC	5 10^{-3}	NC	6 10^{-5}
Largeur de Raie (MHz)	NC	13	NC	9,5
$\Delta\vartheta R(THz)$	NC	9,7	10,5	13
gR(W^{-1} Km^{-1})	NC	1,8 10^{-11}	NC	1 10^{-13}

This study showed to what extent the main non-linear effects in these microstructured chalcogenide fibers could be dominant. This can be an asset when one wishes to make a Raman amplifier. For example, but it can also be a problem due to their power limiting aspect. Suspending core chalcogenide optical fiber also showed excellent non-linear characteristics. For example, their non-linear refractive index is 100 times higher than that of standard silica fiber and this is due to a very strong confinement of the guided mode, thus exacerbating the non-linear effects.

4. Conclusion

Work on the first ten years of FOM was mainly carried out on silica glass fibers. The use of oxyde (telluriul, bismuth or germanium), fluoride and also chalcogenide glasses presents an interesting alternative for transposing the unusual properties of FOM into the mid-infrared (up to 10 μm about), a spectral domain of interest for certain applications in the defence or environmental sectors. Chalcogenide glasses are composed of at least one chalcogen element (S, Se, Te) to which other elements such as Ge, Sb, Ga, As, … can be added. They have a wide range of transparency in the mid-infrared. The optical transmission of FOM can then extend from about 700 nm to more than 12 μm depending on the composition used.

One of the major challenges was to produce FOM made of chalcogenide glass with low optical losses. Initial attemps to manufacture preforms using the stretch bonding technique showed that this was not suitable. An alternative method of preform manufacture by moulding was therefore developed (Figure 2), which resulted in satisfactory transmission levels (Figure 6). Chalcogenide glasses are known to exhibit a high degree of non-linearity, 2 to 3 orders of magnitude higher than that of silica. This property is put to good use in the production of optical sources such as draft or supercontinuum lasers, emitting in the mid-infrared.

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