Mid-infrared extension of supercontinuum in chalcogenide suspended core fibre through soliton gas pumping

J. Fatome, B. Kibler, M. El-Amraoui, J.-C. Jules, G. Gadret, F. Desevedavy and F. Smektala

Reported is an experimental demonstration of the mid-infrared extension of supercontinuum in a 1.9 μm suspended core chalcogenide fibre, the zero dispersion wavelength of which is shifted to 1.9 μm, i.e. into the transparency window of standard silica fibres. Based on the well-known long-pulse regime of supercontinuum generation in silica fibre, a low-cost optical quasi-CW source at 1.53 μm has been converted and shifted into a large number of interacting femtosecond solitons localised up to 2.1 μm. This optical source, called a soliton gas, allows the pumping of a 50 cm long chalcogenide microstructured fibre near its zero dispersion wavelength, thus leading to an efficient extension of a mid-infrared supercontinuum beyond 2.4 μm.

Introduction: Fibre-based supercontinuum (SC) sources in the mid-infrared (mid-IR) have a great potential for many applications such as optical frequency metrology, optical tomography and spectroscopy. It is well known that soft-glass fibres are promising candidates for such devices owing to their low mid-IR losses and high intrinsic nonlinearities as compared to silica [1]. However, the zero dispersion wavelengths (ZDW) of these materials are generally beyond 2 μm and far from the wavelengths of conventional fibre-based laser sources. Consequently, the use of non-silica fibres often requires costly and high-power pump lasers to achieve an efficient spectral broadening up to the mid-IR. During the last decade, research activities have been focused on the development of microstructured optical fibre (MOF) technology for dispersion-tailored waveguides as well as shifting near-infrared lasers to longer wavelengths so as to pump the fibre under test close to its ZDW [1]. In this Letter, we propose to combine both of these attractive options by using the Raman soliton self-frequency-shift process (SSFS) occurring around 1550 nm in a highly nonlinear silica fibre (HNLF) combined with a chalcogenide suspended core fibre the ZDW of which has been shifted from 4.8 to 1.9 μm through its MOF profile in order to extend an SC in the mid-IR region beyond 2.4 μm.

Experimental configuration: The experimental setup is shown in Fig. 1 and is basically made of two stages cascading SC generation towards the mid-IR. The first stage shifts the laser frequency through Raman SSFS, which is commonly used to shift ultrafast 1550 nm pulses to lower frequencies in silica fibres [2, 3]. To this end, we use a low-cost and extremely compact commercial high-power sub-nanosecond pump. Indeed, our passively Q-switched micro-laser delivers 3.7 ns pulses at 1535 nm, with an average power around 19 mW and a pulse repetition rate of 2.7 kHz, corresponding to pulse energy of 7.5 μJ and peak power up to 2 kW. Based on the well-known long-pulse regime of SC generation in silica fibre [4], we take advantage both of modulation instability (MI) and Raman SSFS processes to convert our quasi-continuous-wave (CW) source at 1.53 μm into a large number of interacting femtosecond solitons around 2 μm. The fibre is a 50 m-long segment of highly nonlinear silica fibre (HNLF) characterised by a chromatic dispersion parameter $D = 0.6$ ps/km/nm and a nonlinear Kerr coefficient $\gamma = 10\ \mathrm{W^{-1}\,km^{-1}}$ at the laser frequency. The fibre exhibits a low dispersion slope $D_S = 0.007\ \mathrm{ps/km/nm^2}$ and losses around 0.6 dB/km at 1.55 μm. By using a simple 20× microscope objective (MO) we reach about 40% of coupling efficiency into the HNLF. In this configuration, the SC formation begins with the MI of the continuous pump wave in the anomalous dispersion region, thus evolving into a train of ultra-short soliton pulses [4, 5]. Since MI is a noisy seeded process, the generated solitons will have variable bandwidths and energies. Based on the fibre parameters and the input pump power, we calculate the maximum MI gain at a frequency $\Omega_{max} = 22.6$ THz [6]. In the time domain, the CW is thus converted into a periodic pulse train characterised by a period $T = 2\pi/\Omega_{max} = 45$ fs. The soliton pulses therefore exhibit a temporal width below the period value. Their bandwidth is large enough for intra-pulse Raman scattering to occur leading to a continuous red-shift along the HNLF. Moreover, the different peak powers create a large range of self-frequency shifts, creating a smooth red-shifted continuum [5, 7] (see also next Section). This specific spreading in time and frequency domains of the large number of interacting solitons has been already related to the idea of the soliton gas [5]. The frequency shift of the soliton gas is a function of the HNLF length used and it can be suitably adjusted in order to pump the chalcogenide MOF as close as possible to the ZDW, as shown in the next Section. Note that the long wavelength extent of the HNLF continuum will be limited here by the high losses of silica glass beyond 2.1 μm.

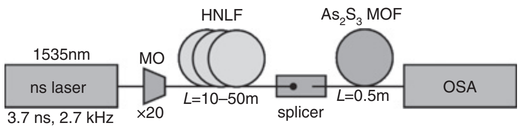

Fig. 1 *Experimental setup of cascaded supercontinuum generation in mid-infrared via soliton gas pumping*

To extend the SC in the mid-IR, the second stage of our setup (see Fig. 1) consists in injecting the resulting HNLF soliton gas into a 50 cm-long segment of chalcogenide MOF designed with a suspended core made of As_2S_3 glass. The input signal was coupled into the chalcogenide fibre by means of the alignment option of an optical fibre splicing device combined with a 3 μm waist micro-lens fibre, which allows an efficient fibre coupling up to 30–40% [8].

Fig. 2*a* shows the corresponding SEM image of the fibre cross-section. Here, the main idea is to use the attractive dispersive and nonlinear characteristics of this small core MOF with a diameter close to 1.9 μm. The calculated dispersion curve of the suspended core MOF is presented in Fig. 2*b* and the ZDW is predicted at wavelengths close to 1.9 μm by taking into account 10% discrepancies on the fibre core size. From our mode calculations, we have also deduced an effective mode area of about 2.4 μm^2 at the ZDW, corresponding to an estimated nonlinear Kerr coefficient $\gamma = 3.86\ \mathrm{W^{-1}\,m^{-1}}$ with $n_2 = 2.8 \times 10^{-18}\ \mathrm{m^2/W}$ [8]. Recently, we have also reported in a chalcogenide MOF that Raman gain is 180 times larger than for fused silica [9], which underlines the potential of this kind of fibre combined with anomalous dispersion for the SSFS process. We thus expect that pumping our suspended core MOF with the soliton gas source in the anomalous dispersion regime will efficiently extend the SC towards the mid-IR by using very short lengths of fibre. Note that our chalcogenide fibre exhibits a large transparency bandwidth in the mid-IR with typical losses about 0.5 dB/m measured in the wavelength range studied [8]. However, extrinsic losses due to impurity absorption (i.e. OH-absorption) affect the glass transmission, which can result in high loss absorption peaks at particular wavelengths such as 1.4 and 1.9 μm, see Fig. 3 and results Section.

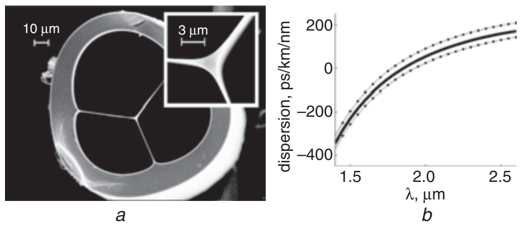

Fig. 2 *SEM image of cross-section of chalcogenide microstructured fibre and (inset) magnification of suspended core, and MOF dispersion curves calculated from microstructure parameters obtained from SEM picture with ±10% accuracy on fibre core size*

a SEM image
b MOF dispersion curves

Results and discussion: The silica and chalcogenide fibres are then chosen and arranged with the final aim of achieving the most significant spectral broadening towards the mid-IR. Fig. 3*a* first shows the experimental results recorded at the output of the HNLF fibre for four different lengths of fibre. As expected, the MI of the continuous pump wave evolving into ultrashort soliton pulses induces intra-pulse Raman self-frequency shifts and subsequently a smooth SC generation. As the length of the HNLF increases, we clearly observe an accumulation of variable bandwidth and energy pulses at the leading edge of the SC qualified as soliton gas [5]. By carefully adjusting the length of the HNLF between 20 and 50 m, we can then localise this soliton gas to around 2 μm in a range of 200 nm. Beyond 50 m, the induced SSFS of the soliton gas reaches the transparency limit of the silica fibre, leading to a rapid decrease of its available energy. Note that the high-frequency part of the SC observed in the HNLF below 1.4 µm in Fig. 3 is generated through dispersive wave formation in the normal dispersion regime. Indeed, the MI-induced solitons are spectrally broad enough such that they overlap with the normal dispersion region of the HNLF (ZDW ~ 1.4 µm), and can excite dispersive waves at phase-matched wavelengths [2, 3].

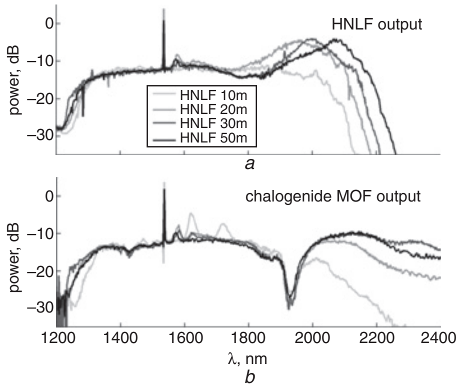

Fig. 3 *Generation of soliton gas at output of HNLF against fibre length, and corresponding supercontinuum extension after soliton gas injection into 50 cm-long chalcogenide MOF against initial HNLF length*

a Generation of soliton gas
b Corresponding supercontinuum extension

When now pumping the 50 cm-long chalcogenide MOF with the different soliton gas described above (Fig. 3*b*), we clearly observe that the SSFS phenomenon starts again so as to extend the initial SC beyond 2.4 µm (limit of our OSA), which proves that the chalcogenide fibre is pumped into its anomalous dispersion regime. Note that for the 10 m-long HNLF configuration, the residual energy contained inside the 1535 nm nanosecond pump is then sufficiently high to generate two spontaneous Raman Stokes components in the chalcogenide MOF (Fig. 3*b*, lightest grey solid line). Finally, the optimum SC extension in the chalcogenide MOF beyond 2.4 µm was obtained for an HNLF length of 30 m and an associated soliton gas localised around 2 µm, which could be interpreted as a ZDW below 2 µm for the chalcogenide fibre. Indeed, this is confirmed by the fact that the SC begins its extension by pumping with the soliton gas localised over the range 1.8–2 µm (10 m-long segment of HNLF).

Conclusions: We have shown that it is possible to extend a silica-based supercontinuum beyond 2.4 µm through the generation of a soliton gas inside an HNLF and its injection beyond the ZDW in a 50 cm-long chalcogenide suspended core MOF. These results reveal that the concatenation of suitably designed optical fibres, in particular based on different materials, could be an attractive solution in order to generate and extend SC sources in the mid-IR region and especially far beyond the silica transparency limit.

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