Comparative study on fluoride fibers for mid-infrared generation pumped by a Cr:ZnS oscillator

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Abstract. We demonstrate a comparative study on single-mode fluoride fibers for mid-IR generation. We took into consideration examples of ZBLAN fibers from all leading manufacturers. The fluoride fibers were pumped with the 30-fs pulses from a Cr:ZnS oscillator which allowed for Raman soliton generation up to 4 µm and supercontinuum generation up to 5.3 µm.

1 Introduction

Mid-infrared generation above 2 µm is widely used in many scientific areas, including frequency comb metrology, spectroscopy, and LIDAR systems. Since the transmission in typical silica fibers transmission is limited up to 2.6 µm, a platform of soft-glass fibers including fluoride, chalcogenide, and telluride fibers, has been developed for mid-IR generation. Fluoride glass fibers possess optimal parameters to form optical solitons or supercontinuum when pumped with femtosecond laser sources. The combination of anomalous dispersion in fluoride fibers and self-phase modulation allows for the formation of optical solitons through the soliton self-frequency shift (SSFS) effect.

To obtain a far spectral tuning range and low soliton order, it is crucial to use a seed source generating short pulses at long wavelengths. The Cr:ZnS oscillators that can emit few-cycle pulses in spectral range > 2 µm [1] make a perfect choice, overcoming limitations resulting from using Er/Tm fiber lasers, or optical parametric amplifiers (OPA). These setups have already been reported [2,3]. In this work, we present a comprehensive study of different fluoride fibers provided by all the leading manufacturers. We demonstrate the generation of SSFS up to 4 µm and the supercontinuum up to 5 µm. To the best of our knowledge, this is the broadest spectral range obtained for both, the Raman solitons, and the supercontinuum phenomena generated in ZBLAN fibers with Cr:ZnS oscillator pumping.

2 Experimental results

The core of our experimental setup is a Kerr-lens mode-locked Cr:ZnS laser oscillator as depicted in Fig. 1. It delivers 30 fs pulses with an average output power of 650 mW. Its repetition rate is set to 25 MHz, resulting in a single pulse energy of 26 nJ. Laser output is spectrally centered at 2.3 µm and covers the range from 2 to 2.6 µm [4]. To prevent back reflections from the fiber face, which disturb stable mode-locked operation, we have employed an optical isolator (ISO). The input optical power entering the fiber reaches 380 mW at maximum.

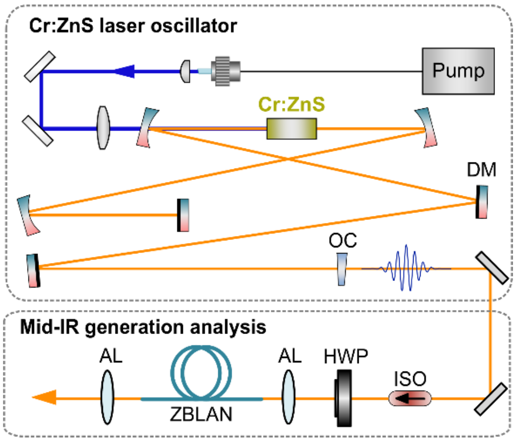

Fig. 1. The schematic of an experimental setup. DM: dichroic mirror; OC: optical coupler; ISO: isolator; HWP: half-wave plate; AL: aspherical lens.

The examples of gathered fluoride fibers, with their parameters including core diameter, length, and dispersion, are listed in Table 1.

Table 1. Fluoride fibers with their parameters.

Manufacturer	Core diameter [µm]	Length [m]	Dispersion β_2 [ps^2/km]
Le Verre Fluore	7.5	14	-25.3
FiberLabs	6.3	0.09	-6.49
	6.6	3	-13.2
	6.8	3	-17.1
Thorlabs (2) InF_3 P3-32F-FC-2	9	2	-24.0
Thorlabs (1) InF_3 P3-23Z-FC-5	9	5	-30.4

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We chose one fiber from Le Verre Fluore with core diameters of 7.5 µm and a fiber length of 14 m. Then, three optical fibers from FiberLabs that differ in core diameter between 6.3 and 6.8 µm, and, hence, also dispersion and nonlinearities. The last two fibers were Thorlabs InF_3 fluoride fibers.

2.1. Soliton generation

Fibers from Le Verre Fluore, two from FiberLabs, and Thorlabs are able to support soliton formation. Due to different dispersion properties, as well as the nonlinear refractive index, n_2, the spectral range of generating solitons differs significantly. Two InF_3 fibers (Thorlabs P3-32F-FC-2 and P3-23Z-FC-5) feature the shortest wavelength tuning, only up to 3.2 µm. This may be due to the largest core diameter, and the smallest value of n_2. Next, there is a fiber with a core of 7.5 µm which can support soliton formation to the wavelength of 3.5 µm. The spectral coverage of all tested fluoride fibers is depicted in Fig. 2. The best wavelength tuning is offered by both fibers from FiberLabs, with core diameters of 6.6 and 6.8 µm. The latter has already been reported to provide a wide shift up to 3.85 µm by N. Nagl in [2].

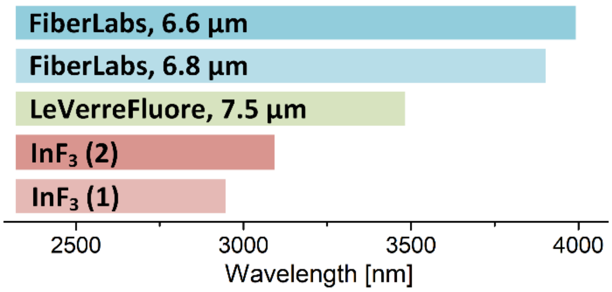

Fig. 2. Spectral range of Raman solitons generation in fluoride fibers when pumped with femtosecond pulses.

The optical spectra of the solitons generated in the fiber with the 6.6 µm core diameter for different input powers of the laser are depicted in Fig. 3. By changing the oscillator's power, one can obtain generation of solitons up to 3990 nm.

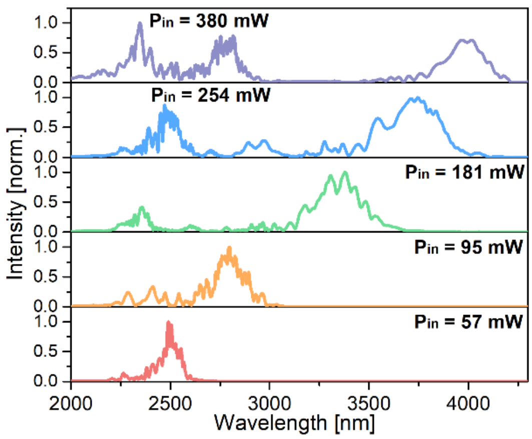

Fig. 3. Optical spectra of frequency-shifted solitons for input powers between 57 and 380 mW.

The conversion efficiency is between 33-44%. It is important to note that the higher-order soliton starts appearing only for the highest input power, 380 mW. It is a result of pumping with an ultrashort pulse, and enables most of the energy to be converted to the fundamental soliton.

2.2 Supercontinuum generation

The last fiber, with a core diameter of 6.3 µm, was used to generate supercontinuum. Due to its very small value of β_2 at 2300 nm wavelength, the fiber supports the broadening of the pulses' spectra over the wavelength range of 1.5-5.3 µm. The short length of the fiber (9 cm) allows it to obtain a smooth and flat spectrum despite the anomalous dispersion regime as it has been analyzed in [5]. The optical spectrum is presented in Fig. 4.

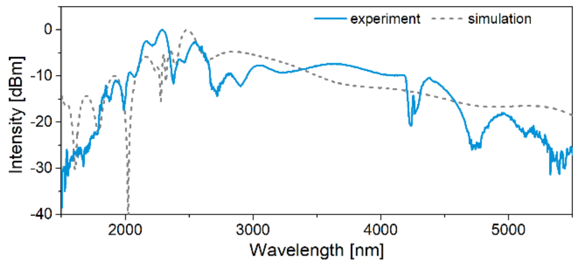

Fig. 4. Simulated (dashed line) and measured (blue solid line) optical spectrum of supercontinuum generated in fluoride fiber qith 6.3 µm core.

To summarize, we achieved the broadest generation of supercontinuum and solitons in ZBLAN fibers for the Cr:ZnS pumping setups. Pulses generated at such a long spectral range can be successfully used in many applications including seeds for OPA systems, spectroscopy, or other time-resolved measurements.

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