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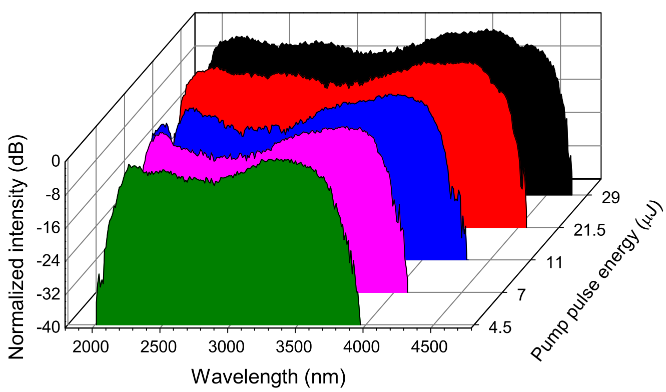

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Mid-infrared Supercontinuum Generation to ~4.7 μm in a ZBLAN Fiber Pumped by an Optical Parametric Generator

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Abstract: We present mid-infrared (mid-IR) supercontinuum (SC) generation from a step-index fluorozirconate fiber pumped at 2.25 μm. When 70 ps pulses with a peak power of 128 kW were launched into a ZBLAN fiber with a zero dispersion wavelength at 1.603 μm, SC was extended to 4695 nm, with spectral flatness below 10 dB, in the 2.00–4.56 μm range. To the best of our knowledge, this is the first time such a broad and flat mid-IR SC spectrum from a ZBLAN fiber pumped with ps pulses has been achieved. The SC evolution as a function of pump wavelength and pump pulse energy was also experimentally demonstrated.

Index Terms: Supercontinuum generation, fiber non-linear optics.

1. Introduction

Mid-Infrared (mid-IR) SC laser sources have attracted significant attention mainly owing to applications in areas such as remote sensing [1], stand-off detection of targets [2], directional infrared countermeasures [3], and medicine [4]. To achieve SC generation in the mid-IR spectral region ($\lambda > 2$ μm), soft glass fibers including tellurite [5], fluoride [6]–[8], and chalcogenide [9], [10] have been successfully used. Among the three fiber families, chalcogenide and fluoride fibers are more mature, and have been commercialized recently. Chalcogenide fibers are transparent in the mid-IR, even up to 15 μm, and their nonlinearity is reported to be more than 200 times stronger than that of silica [11]. They are mechanically and chemically durable, thermally stable, and can be drawn into low-loss fibers both in conventional solid-core/clad and micro-structured fibers. On the other hand, they exhibit a low physical strength, low transition temperature, and low damage threshold, which becomes critical when W-level SC is required. Therefore, many applications, such as those mentioned above, use fluoride fibers including fluorozirconate (ZrF_4–BaF_2–LaF_3–AlF_3–NaF, commonly known as ZBLAN) and fluoroindate (InF_3), supporting SC generation in the 2–5 μm range [12], [13]. These media have made tremendous progress, as a result of their unique properties, such as a wide transmission window, theoretical losses at least one order of magnitude lower than those of silica fibers (0.01 /km between 2 and 3 μm), low optical dispersion, a low refractive index, and the possibility of machining and polishing. Their main drawback is a low resistance to moisture, leading to a degradation in air with prolonged exposure.

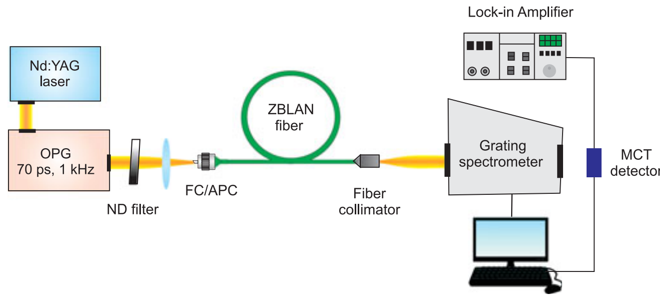


Fig. 1. Schematic of the mid-IR SC generation system.

Supercontinuum generation in fluoride fibers pumped with femtosecond [13], [14], picosecond [15], [16], and nanosecond [7], [17] pulses has been reported during the last decade. An ultra-wide SC spectrum extending from ultraviolet to 6.28 μm [13], as well as an SC source emitting an average power as high as 24.3 W [18], generated out of ZBLAN fibers, have been demonstrated. Furthermore, it has been shown that single-mode fluoride fibers can be successfully fusion-spliced with other fluoride fibers [12] and even with silica fibers [19], [20], providing an all-fiber format for an SC source. Notwithstanding such impressive results, selecting a proper nonlinear medium and pump pulse parameters that affect the efficiency of broadband mid-IR SC evolution, featured by high flatness and a long cut-off wavelength, remains a challenge.

In this paper, we report what we believe to be the first demonstration of flat and broadband mid-IR SC spectrum from a single-mode, step-index ZBLAN fiber directly pumped with high-peak power picosecond pulses. The optimized output SC spectrum covered the band up to ∼4.7 μm, with 10 dB spectral flatness in the 2000–4560 nm mid-IR region.

2. Experimental Setup

The experimental arrangement for SC generation is shown in Fig. 1. A narrow linewidth optical parametric generator (OPG) manufactured by EKSPLA (PG711/DFG-SH) was utilized as a pump source. The system, consisting of an optical parametric oscillator (OPO) and an optical parametric amplifier (OPA), delivered ∼70 ps laser pulses with nearly Fourier-transform-limited linewidth ($0.5\,cm^{-1}$) and a pulse repetition frequency of 1 kHz. The output wavelength tuning range covered the spectrum from 1.55 μm up to 16 μm and was divided into three spectral sub-bands: 1550–2020 nm (signal), 2250–3350 nm (idler), and 3350–16000 nm (signal and idler mixed in a GaSe crystal). The OPG was synchronously pumped by a high power 1.064-μm-wavelength mode-locked Nd:YAG laser (PL2210B-TR-P100, EKSPLA).

The laser radiation from the OPG was focused and launched into a ZBLAN fiber (manufactured by Le Verre Fluore) through a CaF_2 lens. A continuously variable reflective neutral density (ND) filter provided the adjustable attenuation of the pump radiation at different wavelengths, thus enabling the pulse energy adjustment. The output from the fluoride fiber was collimated by a CaF_2 lens with the focal length of 20 mm. The SC spectra were measured using a Horiba iHR-320 spectrometer with an HgCdTe (MCT) detector (VIGO System S.A.), with a frequency bandwidth of 40 MHz. To increase the dynamic range of spectral measurements, the detector was connected to a lock-in amplifier (SR530, Stanford Research Systems). To prevent second order diffraction of the grating installed in the spectrometer, suitable long-pass filters were used. The spectral resolution of the measurements was 10 nm.

The customized step-index ZBLAN fiber, used as a nonlinear medium, was characterized by a core/clad diameter of 6.8/125 μm, a numerical aperture (NA) of 0.23, and a cut-off wavelength of 2.04 μm. The fiber loss in the 1.3–3.75 μm band was below 0.05 /m, with a minimum of 1.4 dB/km at 2.54 μm, and rapidly increased for longer wavelengths, up to 0.2 dB/m and 5 dB/m at 4 μm and 4.5 μm, respectively.

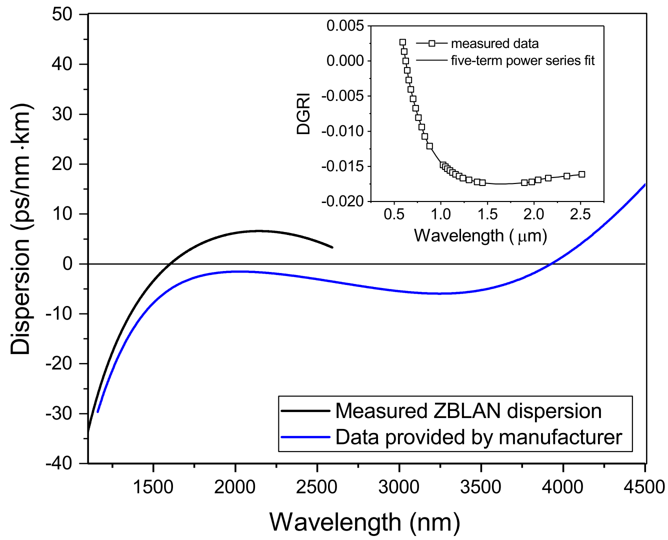


Fig. 2. Calculated and measured dispersion characteristics of the ZBLAN fiber. (Inset) Measured differential group refractive index (DGRI).

Information about the dispersion of a nonlinear fiber, in particular the location of the zero dispersion wavelength (ZDW), is of key importance for SC generation efficiency [21]. The dispersion of the ZBLAN fiber used in the experiment was measured applying a simple technique, based on spectral interferometry and employing a FT-NIR spectrometer (ARCoptix). The method utilizes a SC source (SC450-4, Fianium), a dispersion balanced Mach-Zehnder interferometer and a fiber under test of known length placed in one arm of the interferometer while the other arm has adjustable path length. The method is based on recording a series of spectral interferograms to measure the differential group refractive index (DGRI) as a function of the wavelength [22], [23]. Then, this dependence is fitted to the approximate function enabling to obtain the chromatic dispersion. The measurements were performed for the wavelength range only up to 2.5 μm due to the limited bandwidth of the SC source that was used. The dispersion characteristic of the nonlinear fiber is shown in Fig. 2. The inset shows the measured DGRI. As can be seen, the dispersion, starting from 1.12 μm, grows steeply reaching the ZDW at 1603 nm. The maximum of the dispersion curve (6.6 ps $\cdot$ nm^{-1}$\cdot$km^{-1}) was measured to be at 2.15 μm. For longer wavelength the dispersion starts to drop reaching 4.5 ps $\cdot$ nm^{-1}$\cdot$km^{-1} at 2.5 μm (upper measurement limit). The second ZDW is expected at 2.78 μm. For comparison, the calculated dispersion curve of the ZBLAN fiber, provided by Le Verre Fluore, was also included in the graph presented in Fig. 2. In this case the dispersion profile of the fluoride fiber was found numerically according to the algorithm presented in [24]. Comparing the two curves in the wavelength range of 1.2–2.5 μm it can be noticed that they are similar, except that the calculated curve is shifted down by up 8 ps$\cdot$nm^{-1}$\cdot$km^{-1}. The measurements of the fiber dispersion for wavelengths longer than 2.5 μm will be the subject of our future research.

Both ends of the fluoride fiber were installed in specialized FC/APC bare fiber adapters and hand-polished at an angle of 8° to avoid unwanted damage caused by Fresnel reflections. They were also checked using a microscope to ensure a good quality of their facets.

3. Results and Discussion

To obtain efficient broadband SC generation, a nonlinear fiber should be preferably pumped in the anomalous dispersion region relatively close to the zero group velocity dispersion (GVD) point [21]. In our case, as shown in Fig. 2, the ZBLAN fiber was designed and manufactured with the ZDW at 1.603 μm and it was pumped at different wavelengths from 1.7 μm to 2.9 μm. Applying different

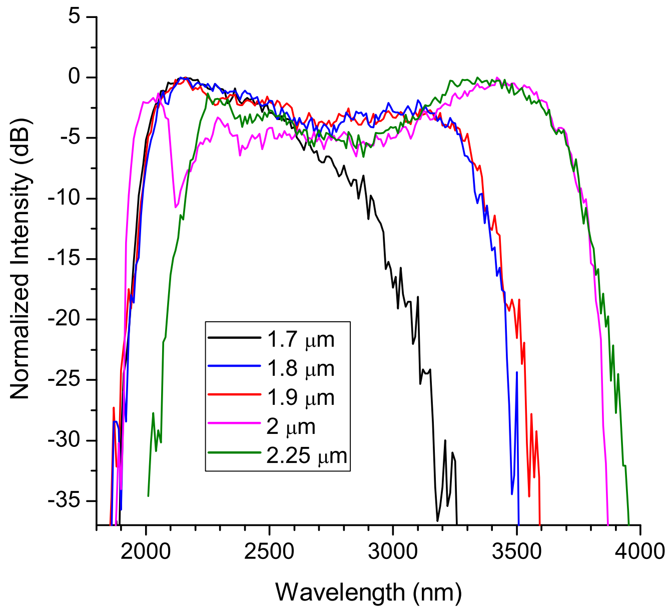


Fig. 3. SC spectra for a 3-m long ZBLAN fiber for different pump wavelengths tuned from 1.7 μm to 2.25 μm. The pump pulse energy was ∼4.5 μJ.

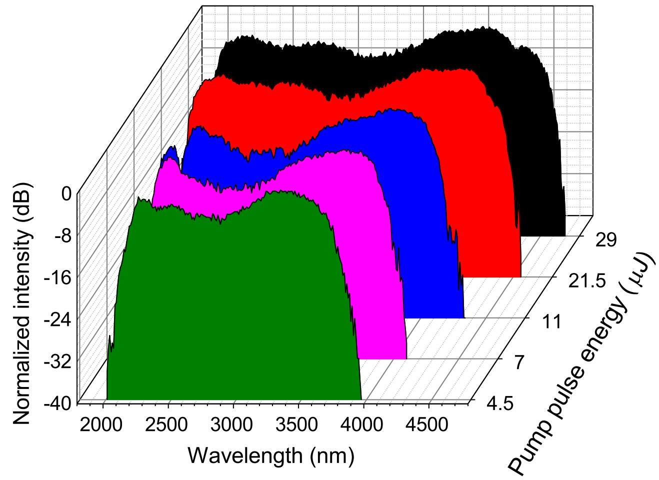
pump wavelengths and different pumping pulse energies allowed determining optimal pumping conditions for the fiber that was being used. The results of these investigations are summarized in Figs. 3–5.

Fig. 3 shows the SC spectra generated out by a 3-m long ZBLAN fiber for different pump wavelengths corresponding to the fiber dispersion in the anomalous region, while the incident pulses energy was ∼4.5 μJ, in an attempt to keep it constant. The pulse energy was measured using a pyroelectric laser energy sensor (PE10, Ophir) and was adjusted using the ND filter located at the OPG output. Each SC spectral measurement was preceded by a coupling adjustment. All spectra were measured beyond a long pass filter with a wavelength edge at 2 μm.

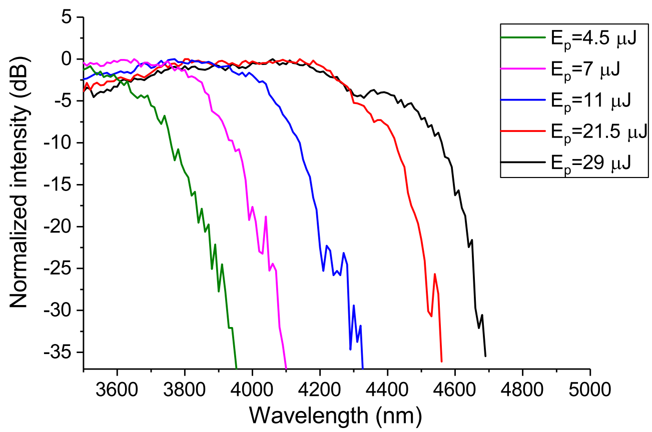
The pump wavelengths of 1.7 μm, 1.8 μm, and 1.9 μm yielded the spectra that extended up to 3160 nm, 3480 nm, and 3500 nm, respectively. The broadest SC spectrum, extending to 3870 nm, was obtained when the ZBLAN fiber was pumped at 2 μm; however, the longest cut-off wavelength (3950 nm) was achieved for the 2.25-μm-wavelength pump. The dispersion values for the two wavelengths were very similar (approximately 6 ps·nm^{-1}·km^{-1}), but the losses in the 2.25-μm-wavelength case equaled 2 dB/km, which is more than one order of magnitude smaller comparing with the losses in the 2-μm-wavelength case (30 dB/km), which was crucial at the beginning of SC generation process, affecting its further efficient evolution. We also pumped the nonlinear fiber at 2.45 μm and 2.9 μm, but for these cases we did not achieve such efficient spectrum broadening, which partially can be attributed to lower coupling efficiency of pump pulses at longer wavelengths. These cases need to be analyzed more deeply, which will be the subject of our further research.

In the next investigation, which addresses the dependence of the output SC spectrum generation on the pump pulse energy, we applied only the 2.25-μm-wavelength pump. Some results are shown in Fig. 4.

Increasing the pump pulse energy from 4.5 μJ to 29 μJ, extended the long wavelength edge of the SC spectrum to 4695 nm. The maximal peak power of the pump pulse launched into the fiber, assuming a Gaussian-shaped pulse, was calculated to be 128 kW. In the system arrangement applied, the SC output average power was up to several mW. The spectral range was considered according to the noise level of the detection system. The SC evolution at wavelengths shorter than 2 μm was not investigated, mainly owing to the detection system limitations. Nevertheless, it has



(a)



(b)

Fig. 4. Output SC spectrum evolution with the pump pulse energy for a 3-m long ZBLAN fiber pumped at 2.25 μm. (a) Spectra recorded in the entire detection band. (b) Spectra of the SC long wavelength side.

already been shown that using fluoride fibers it is possible to achieve a broadband SC spectrum with a short-wavelength edge below 1 μm [6], [13], [25]. Further increasing the pulse energy resulted in the fiber end-face damage. It is worth noting that after being destroyed the fluoride fiber was re-polished and re-used in the experimental setup. In both cases the fiber damage occurred when the pulse energy exceeded 31.5 μJ, yielding a critical power density of ~410 GW/cm^2.

In the experiment power conversion efficiency to selected mid-IR wavelength regions and stability of the generated SC spectrum were not determined, mainly due to the measurement system limitations.

Finally, we investigated the optimization of the fluoride fiber length, setting the pump wavelength at 2.25 μm and the pump pulse energy at 29 μJ. To this end, we used three pieces of the ZBLAN fiber with the lengths of 3 m, 6.25 m, and 12 m. The recorded spectra, measured beyond a 2-μm-wavelength long-pass filter, are plotted in Fig. 5.

Selecting the proper length of a nonlinear fiber is crucial for optimizing the SC bandwidth. As can be seen in Fig. 5, the broadest spectrum at the cut-off wavelength of 4695 nm was generated by a 3-m-long fiber. The 6.25-m-long and 12-m-long fibers yielded spectra that reached 4600 nm and 4425 nm, respectively. The SC long-wavelength edge is consistent with the intrinsic ZBLAN material losses. For ZBLAN fibers attenuation for wavelengths over 4 μm rapidly increases, strongly

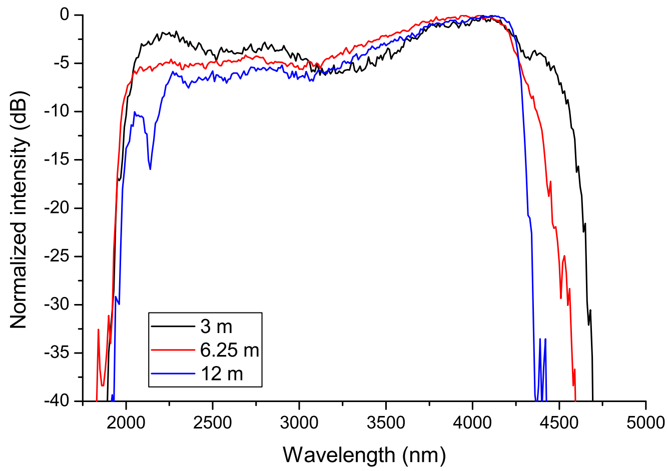


Fig. 5. Optimization of the SC generation by varying the ZBLAN fiber length for the pump wavelength of 2.25 μm. The pump pulse energy was ∼29 μJ.

attenuating red wavelengths generated in longer fibers and preventing long wavelengths cut-off extension. The 10 dB flatness of the SC spectrum generated at the end of the 3-m-long ZBLAN fiber remained in the mid-IR region, in the 2.00–4.56 μm range, without revealing a residual peak at the pump wavelength.

The fluoride fiber was pumped with picosecond pulses in the anomalous dispersion region, which means that mechanisms leading to the continuum generation in this case relied primarily on modulation instability (MI) leading to the pump pulse breakup and the generation of a distributed spectrum of many solitons that were further red-shifted when interacting with the nonlinear medium. As the MI process is noise driven, a distribution of many solitons, with different energies, was created resulting in different rates of self-frequency shifting. They were additionally broadened by self-phase modulation and cross-phase modulation making the SC spectrum relatively smooth and flat.

4. Conclusion

In conclusion, mid-infrared SC generation reaching 4695 nm, with a spectral flatness better than 10 dB in the 2.00–4.56 μm range, was demonstrated. A step-index ZBLAN fiber with a ZDW at 1.603 μm, pumped with 70 ps pulses at the wavelength of 2.25 μm, was used as a nonlinear medium. To the best of our knowledge, this is the first report on such a flat and broadband mid-IR SC generation using a ZBLAN fiber pumped with picosecond pulses. The SC evolution in the ZBLAN fiber as a function of pump wavelength and pump pulse energy was also demonstrated. The ZBLAN fiber damage threshold was experimentally found to be ∼410 GW/cm^2.

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