Recent Development of Mid-Infrared Supercontinuum Generation in Fluoroindate Glass Fibers

Jacek Swiderski

Institute of Optoelectronics, Military University of Technology, 2 gen. S. Kaliskiego Street, 00-908 Warsaw, Poland; jacek.swiderski@wat.edu.pl; Tel.: +48-261839842

Abstract: Supercontinuum (SC) generation that leads to the emission of broadband radiation has been extensively studied. In particular, SC sources encompassing the wavelength range of 2–5 μm have attracted considerable interest in the last decade, and a continuous increase in the output power and spectrum width has been observed. To enable broadband and high-power SC generation, suitable nonlinear media combined with appropriate pump sources must be used, maintaining the output as spectrally flat. This paper briefly reviews the current state-of-the-art SC sources restricted to those based on fluoroindate fibers, including systems pumped with femtosecond, picosecond, and nanosecond pulses. First, the concept of SC generation in optical fibers is briefly presented. This is followed by an examination of indium fluoride optical fibers, with an emphasis on their material and waveguide properties. Furthermore, the advances in SC generation in fluoroindate fibers, including the latest results on high-power (Watt-level) continuum generation adopting different pump schemes, are also explored. A record time-averaged output power of 11.8 W with a spectrum spanning from ~1.9 to 4.9 μm has been demonstrated, which is certainly not the power limit of this technology. Finally, potential future directions of research are discussed at the end of this paper.

Keywords: supercontinuum generation; mid-infrared; fluoroindate fibers; nonlinear optics; fiber lasers; fiber amplifiers

1. Introduction

Mid-infrared (mid-IR) supercontinuum (SC) generation has attracted considerable interest in recent years, owing to its advantageous applications in many important fields of science and industry. First, this spectral range covers the characteristic absorption lines of several versatile materials and important molecules (e.g., CO₂, HCl, CH₃, CH₄, O₂, NO, and NO₂) [1,2], leading to the adoption of mid-IR SC sources for imaging [3], spectroscopy [4–6], and remote sensing, including the remote detection of explosives and hazardous chemicals [7,8]. The improvements in these sources have also paved the way toward new possible applications in defense [3,9], utilizing directional infrared countermeasure (DIRCM) systems, where a collimated output beam can be used to blind an infrared detector of a heat-seeking missile [10–12]. Finally, their use in medicine (e.g., tissue ablation, coherent anti-Stokes Raman scattering (CARS) microscopy, and breath diagnostics) [13–18] as well as in the generation of few-cycle optical pulses in the mid-IR region [19–21] or for the stabilization of frequency comb lasers [22] are also worth mentioning. Some of the aforementioned applications require laser sources that deliver high-quality, high-power beams with a broadband and flat spectrum covering the entire 2–5 μm band. Therefore, research on such laser systems providing high spectral brightness, defined as the radiance per unit optical bandwidth, has been the primary focus in many laboratories.

Supercontinuum generation is a phenomenon, first described in the 1970s [23,24], in which high-intensity laser pulses launched into a nonlinear optical medium interact with
it, leading to the emission of new light frequencies and, eventually, causing the output spectrum to be much broader than the spectrum of the pump radiation. The efficiency of this process depend on many factors, including the peak power of the irradiated pulses, nonlinearity, dispersion, transmission band, losses, and the interaction length of light with a nonlinear medium. Considering these issues, low-loss optical fibers are preferred for SC generation because they provide effective laser beam confinement in a small fiber core area over its entire length. A schematic of SC generation is shown in Figure 1.

![Figure 1. Schematic setup for SC generation.](image)

An SC is usually generated by pumping a nonlinear fiber with high-intensity femtosecond pulses delivered by mode-locked lasers. Spectral broadening of the propagation of light pulses is attributed to a combination of various third-order nonlinear effects, such as self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), dispersive-wave generation (DWG), and stimulated Raman scattering (SRS) [25]. Although this approach can lead to the generation of a wide continuum, the output power is usually limited to only the milliwatt level. To achieve higher output powers, laser systems that provide picosecond and nanosecond pulse trains with a high average output power must be employed.

The dynamics of the SC generation process depends on the relationship between the duration of the pump pulse, the emission wavelength of the laser source, and the zero-dispersion wavelength (ZDW) of a nonlinear fiber [26]. When a fiber is pumped with femtosecond pulses in the anomalous dispersion region, such that the pump wavelength is longer than the ZDW of the nonlinear material, the spectrum broadening is determined mainly by soliton fission and soliton self-frequency shift (SSFS) [27,28]. By pumping an optical fiber with ultrashort pulses in the normal dispersion region, the SC generation mechanism is dominated by SPM. In the case of SC sources pumped with longer pulses (of the order of picoseconds and nanoseconds) at a wavelength corresponding to the anomalous dispersion regime, the emission of new frequencies is initialized with SPM and modulation instability (MI) [29], manifesting as a disintegration of the long pulses into a distributed spectrum of femtosecond sub-pulses during propagation in the fiber core. In the second step, the ultrafast sub-pulses are red-shifted toward the mid-IR region via soliton dynamics, such as soliton fission and soliton frequency shift, owing to the Raman effect [25,29]. The dominant physical mechanisms underlying SC generation in a fiber pumped with longer pulses in the normal dispersion region are essentially FWM and Raman scattering [29,30].

The choice of a nonlinear material that can be considered for SC generation is determined by a number of parameters, such as the transmission band, nonlinearity, ability to handle high optical power, availability of materials of sufficient quality, and maturity of fiber manufacturing technology that is particularly important, considering practical aspects. To date, silica-based fibers are the predominant nonlinear media for SC generation, mainly owing to their high strength, low losses, high resistance to atmospheric conditions, and above all, their mature drawing technology. Such systems utilizing both passive and active silica fibers have been widely reported over the last decade (see [31–33] for examples). However, the longest emission wavelength that can be generated in this medium is ~2.8 μm, which results from the maximum phonon energy of silica glass (1100 cm⁻¹) [34].
The use of silica glass fibers with high-GeO₂-doped cores has extended the transmission beyond 3.4 µm [35,36]. However, to extend the spectrum toward the mid-IR further, the use of soft-glass fibers (with wider infrared transmission windows), such as fluoride [37–45], tellurite [46–48], and chalcogenide (ChG) (e.g., As₂S₃ and As₂Se₃) [49–55] fibers, is mandatory. Each of these media offers certain advantages and disadvantages, such as ease of manufacture, physical strength, wavelength transmission band, corrosion resistance, and thermal damage.

Fluorozirconate (ZBLAN) fibers have been used for SC generation with an average output power of several tens of watts; however, the output spectrum tends to be limited to ~4.7 µm on the long-wavelength side [38,39,41], which results from intrinsic fiber losses at longer wavelengths. Fluoroindate (InF₃) fibers with lower phonon energy can guarantee an extended transmission window (to ~5.5 µm [56,57]) and the delivery of high average power output beams [58–61]. The recent progress in the drawing technology of single-mode tellurite fibers supporting light transmission in a band of ~0.4–5 µm allows considering them theoretically as an alternative to fluoride fibers [46,62,63]. Nevertheless, the current literature reports show that increased material absorption is related to water retention, and, consequently, a reduced damage threshold still hinders the scaling up of the SC power in this medium. Recently, an SC output power of 22.7 W generated from a fluotellurite fiber was also demonstrated [64], but in this case, the spectrum long-wavelength edge (LWE) was limited to 3.95 µm. For all aforementioned soft-glass fibers, the LWE of the spectrum is determined by the multiphonon absorption of the nonlinear medium. To achieve emission at wavelengths beyond this edge, short fiber lengths and pumping with high-intensity pulses are required. This approach is typically implemented in a laboratory environment.

Currently, the broadest SC spectra can be generated in ChG fibers with an extremely high nonlinear refractive index nₑ that is approximately two orders of magnitude higher than that of fluoride fibers [65]. Although ChG fibers yield an extremely broad mid-IR SC spectrum, even exceeding 10 µm [49,50,66], the overwhelming number of demonstrations to date concern light emission at the milliwatt level. Nonetheless, recent reports on SC generation in As₂S₃ fibers show that output power scaling up to over 1 W with an LWE over 6 µm is possible [67,68]. Further upscaling of average output SC power is also expected, particularly because the damage threshold for arsenic sulfide fibers is rather high, reaching ~2.9 GW/cm² for 2 ns pulses at 1.9 µm [69] and over 1000 GW/cm² for 150 fs pulses at 3 µm [70,71].

It is well-known that to achieve efficient spectrum broadening, particularly extending toward the mid-IR region, it is necessary to pump a nonlinear medium in the anomalous dispersion region, relatively close to its ZDW [25,30]. In the case of most available step-index ChG fibers, the material ZDWs are usually located at wavelengths longer than 4.8 µm that are far away from the emission wavelengths of most available laser sources doped with Er³⁺, Tm³⁺, and Ho³⁺ ions. Consequently, such pumping does not offer optimum broadband SC emission and usually requires the use of complex and expensive optical parametric oscillators (OPOs). In the case of fluoride fibers, the choice of pump sources is wider. Both fluorozirconate and fluoroindate step-index fibers exhibit a ZDW within the wavelength range of ~1.5 to 2.1 µm, covered by the widely available and powerful pulsed laser systems. The advantage of InF₃ fibers over ZBLANs is the wider transmission band that renders them ideal candidates for high-power SC generation in the 2–5 µm atmospheric window.

2. Fluoroindate Fibers—Design and Material Properties

Fluoride glass fibers were discovered at Rennes University in 1974 [72], and since then, these media have made tremendous progress toward commercialization. They are well-suited for high-power applications in the 2–5 µm wavelength range and have mainly been used as active media for laser oscillators [73–76], nonlinear media for SC generation [39,41,77], and laser power delivery [78,79]. The most widespread heavy-metal fluoride
glass is ZBLAN (ZrF$_6$–BaF$_2$–LaF$_3$–AlF$_3$–NaF), which is a highly stable material for high-quality optical fibers [80]. ZBLAN fibers are able to transmit more than 20 W in a singlemode core [41], but the maximum broadening is limited to ~4.7 μm, as already mentioned [81]. To overcome this limitation and extend the spectrum LWE to over 5 μm, fluoroindate glass fibers have been considered the best choice.

Fluoroindate or indium fluoride (InF$_3$) glass fibers have a maximum phonon energy of ~510 cm$^{-1}$ [82,83] compared with ~579 cm$^{-1}$ for fluorozirconate glasses [84,85], and thus, they can provide a transmission window with an LWE extended to ~5.5 μm. They also exhibit a higher damage threshold than ChG fibers [83]. Moreover, fluoroindates have a glass transition temperature (Tg) of ~300 °C [57,81]; that is, higher than those of ZBLANs (Tg ~ 260 °C [86,87]) and ChG glasses (Tg ~ 185 °C for As$_2$S$_3$; Tg ~ 178 °C for As$_2$Se$_3$) [88]. The refractive index of these glasses is within the range of 1.47–1.53 [89,90], comparable to that of silicates, indicating that the Fresnel loss is less than 4%. The nonlinear refractive index $n_2$ has been recently determined to be 3.2–4.3 × 10$^{-19}$ m$^2$/W [91]; that is, 1.5× higher than that for ZBLAN fibers and an advantage in the context of SC generation.

Currently, InF$_3$ glass can be drawn into high-quality optical fibers. There are three commercial manufacturers of single-mode fluoride fibers (Le Verre Fluoré, Thorlabs, and FiberLabs); however, only two offer single-mode InF$_3$ fibers. Figure 2 shows the attenuation curves of InF$_3$ fibers obtained from two different producers as a function of the wavelength. The commercially available fiber offered by Thorlabs exhibits losses < 0.2 dB/m for all wavelengths between ~1.6 and 4.6 μm with a minimum value of ~0.03 dB/m at ~3.6 μm. However, the attenuation of the custom-made fibers could be even lower. For instance, Le Verre Fluoré provides InF$_3$ fibers with losses as low as 0.02 dB/m within the wavelength band of ~1.9–4.1 μm. For all the presented fibers, for wavelengths over 4.8 μm, the material losses significantly increase, reaching more than 0.6 dB/m at 5 μm. The main contribution to absorption is made by the OH$^-$ groups at a wavelength of ~2.9 μm [92]. Multiphonon absorption is predominant beyond 4 μm.

![Figure 2](image.png)

Figure 2. Attenuation spectra of selected single-mode fluoroindate fibers (data provided by manufacturers [93,94]).

The currently available single-mode fluoroindate fibers have cores with diameters ranging from 7 to 16 μm and an NA of 0.14–0.3, and they are drawn by applying the mainstream preform technique. Drawing parameters yielding high-quality optical fibers are critical; however, they are difficult to control [56]. In particular, impurities and
moisture in the atmosphere during the preparation of fluoride glasses can easily induce crystallization, leading to the generation of scattering centers and increased losses [95]. It is obvious that the entire process, including the purity of the starting materials, glass synthesis, preform preparation, and fiber drawing conditions (such as control of the heating zone length, extrusion temperature, and chemo-mechanical treatment), must be optimized to achieve low fiber losses [57]. There is scope for improvement because the achieved attenuation level is much lower than the theoretical level.

The dispersion of InF₃ fibers is similar to that of ZBLANs. The material dispersion of InF₃ fibers crosses zero at ~1.8 μm [90,96] and monotonically increases with the wavelength; exemplary dispersion curves are shown in Figure 3. It should be noted that the material dispersion of each glass composition is inherent and cannot be changed. However, the total fiber dispersion also depends on the waveguide dispersion, implying that with suitable fiber engineering techniques, such as manipulation of the fiber core diameter and NA, it can be flattened or the ZDW can be shifted to shorter or longer wavelengths.

![Figure 3. Dispersion profile of single-mode fluoroindate fibers manufactured by Thorlabs (a) [94] and Le Verre Fluore (b). (b) Reproduced with permission from [59]. Copyright 2018, Chinese Laser Press.](image)

Another issue addressed in fluoroindate fibers is their mechanical strength, which is much lower than that of silica fibers [89]. Their fragility results from extrinsic defects, such as microcrystals, microbubbles, and core–cladding interface imperfections [97]. However, in recent years, the strength of all fluoride fibers has been significantly improved, allowing the user to stripe, cleave, and even fusion-splice them [42]. Furthermore, to enhance their strength, the fibers can be coated with Kevlar or stainless-steel jackets and connected with different types of connectors (e.g., FC/PC, FC/APC, and SMA-905). Furthermore, InF₃ glass fibers have enhanced stability in atmospheric moisture compared with ZBLANs, owing to the lack of the NaF component. Thus, they satisfy the requirements of many industrial applications.

Excellent reviews of InF₃ glasses are presented in refs. [90,92,96,98,99], whereas more information about InF₃ fibers can be found in refs. [56,57,81,83,89,97,100].

3. Mid-Infrared Supercontinuum Generation Using Femtosecond Pulses

The optimal pump source for SC generation is a mode-locked laser that emits the high-peak-power pulses necessary to trigger the nonlinear processes responsible for continuum evolution. Such pulses can be generated directly by single oscillators as well as
optical parametric generators (OPGs) and amplifiers. Therefore, it is not surprising that the first demonstration of SC generation in an InF₃ fiber was reported using ultrashort laser pulses. In 2013, Theberge et al. [101] performed an experiment in which an optical parametric amplifier providing 70-fs optical pulses at a wavelength of 3.4 μm was used to pump a 9.5-m-long InF₃ fiber. The nonlinear fiber was characterized by a core/clad diameter of 16/120 μm, NA of 0.14, ZDW at a wavelength of 1.83 μm, and a cut-off wavelength of 2.8 μm.

For the pump pulse energy of 120 nJ (peak power of 1.7 MW), the output SC spectrum spanned from ~2.4 to 4.95 μm with a 20-dB spectral flatness from 2.7 to 4.7 μm (Figure 4). The authors expected further spectral broadening, as the fluoride fiber losses at longer wavelengths were not the dominant factor limiting spectrum extension. The losses at ~4.7 μm were determined to be 0.5 dB/m, and the spectrum decrease was not extremely sharp, as shown in Figure 4. According to the authors, the achieved spectrum width was probably limited by the dispersion of the extremely broad supercontinuum laser pulse generated in the nonlinear fiber.

![Figure 4. Supercontinuum generation in a 9.5-m-long fluoroindate fiber. Adopted with permission from [101]. Copyright 2013, Optica Publishing Group.](image)

Although the spectrum spanned over 2000 nm in the mid-IR window, the authors did not mention the average output SC power. However, considering that such pump laser systems usually operate at a repetition rate of up to several kHz, the output power was at the milliwatt level. It is worth mentioning that the solid-state femtosecond pump source used was relatively large and expensive.

The alternative for OPGs is femtosecond mode-locked Tm-doped fiber lasers. Considering that the ZDW of fluoroindate fibers is usually located below 2000 nm, they could be suitable candidates for pumping fluoride fibers. This architecture also allows easy application of an amplifier, thus offering scaling up of the output SC power. This solution has been demonstrated by Salem et al. [102]. A commercial femtosecond fiber laser emitting at 1560 nm with a 50 MHz pulse repetition frequency (PRF) was used as the seed. After amplification in an erbium-doped fiber amplifier, the pulse train was launched into a highly nonlinear fiber with the aim of shifting more than half of the pulse energy (as a result of SSFS) to approximately 1960 nm. The final part of the pump source was a cladding-pumped thulium-doped fiber amplifier used to increase the average power at wavelengths of approximately 2 μm to 570 mW. A dispersion-compensating fiber (DCF) was used to compensate for the overall dispersion of the active fiber. Assuming a sech²
intensity profile, the output pulse width was calculated to be 97.5 fs. The output spectrum, extended from ~1.9 to 2.25 μm with two intensity peaks around 1.96 and 2.12 μm, is presented in the inset of Figure 5. Furthermore, more than 90% of the pulse energy was red-shifted to approximately 2125 nm. Such a pump signal was launched into a dispersion-engineered indium fluoride fiber having a core diameter of 7 μm, ZDW at 1.9 μm with a small anomalous dispersion at 2.1 μm and over the mid-infrared region to 4.5 μm (<7 ps/nm/km). The output spectrum generated from the nonlinear fiber is depicted in Figure 5.

![SC spectrum and pump signal](image)

**Figure 5.** SC spectrum recorded for the average output power of 247 mW. Adopted with permission from [102]. Copyright 2015, Optica Publishing Group.

Indium fluoride fibers of two lengths of 30 and 55 cm were used in the experiment. The shortest fiber generated an average output power of 258 mW with a 20-dB bandwidth of 2250 nm, whereas the longer fiber generated an output power of 247 mW with a 20-dB bandwidth of 2980 nm. In both cases, the spectrum covered nearly two octaves of bandwidth and extended up to 4.6 μm. It was also observed that increasing the length of the nonlinear fiber further did not increase the generated bandwidth. The ratio of the SC power outside the pump spectral region (shown in the inset of Figure 5) to the total output SC power was calculated to be 70%.

4. Mid-Infrared Supercontinuum Generation Using Optical Parametric Oscillators and Amplifiers Delivering Picosecond Pulses

Continuing the discussion in Section 3, a similar experiment employing an optical parametric oscillator and amplifier system was performed by Michalska et al. [103]. However, in this case, they used longer picosecond-scale pulses with the possibility of output wavelength tunability; thus, the pump radiation could be adjusted in relation to the ZDW of a nonlinear medium.

The pump laser system delivered ~70 ps optical pulses at a repetition frequency of 1 kHz and a maximum pulse energy of 400 μJ at 1.7 μm. The wavelength of the output pulses could be tuned from 1.5 to 16 μm. The step-index, single-mode 9-m-long fluorindate fiber used as a nonlinear medium, featured a core/clad diameter of 9/125 μm, an NA of 0.26, and a cut-off wavelength of 3.2 μm. The fiber exhibited losses below 0.5 dB/m for all wavelengths between 1.7 and 4.8 μm, a ZDW at 1.72 μm, and a flattened dispersion profile (<14 ps-nm²-km⁻¹) over the range of 2 to 4.4 μm.
Supercontinuum generation was investigated as a function of the pump wavelength and pulse energy/peak power launched into the fiber. This allowed the optimal pumping conditions to be determined for the nonlinear medium used. First, the pump wavelength was varied to maintain the pump pulse energy launched into the fiber at a constant level. This allowed the authors to determine the optimal pump wavelength for the nonlinear medium being used, providing efficient SC spectrum extension toward the mid-IR. The broadest spectrum was obtained when pumping at 2.02 μm. In the second part of the study, SC evolution as a function of pump pulse energy was examined while maintaining the pump wavelength at 2020 nm. Figure 6 shows the resulting SC spectra emitted from the InF₃ fiber, recorded for four different pump pulse energies (peak powers).

Figure 6. SC spectra obtained from the InF₃ fiber pumped at 2.02 μm, recorded for injected pump pulse energies of ~2.7 μJ (36.3 kW), 3.9 μJ (52.4 kW), 5.5 μJ (73.9 kW), and 8.3 μJ (111.5 kW). Reproduced under the terms of the Creative Commons CC BY license [103]. Copyright 2016, The Authors, published by Springer Nature.

As expected, the growth of the long-wavelength edge can be observed as a result of the increase in the pump energy. At the highest coupled pulse energy of 8.3 μJ, the spectrum covered the entire 2–5 μm interval with a cut-off wavelength of 5.25 μm, representing an octave of optical bandwidth. The signal drop at ~4.2 μm corresponds to absorption by CO₂ molecules in the detection system. The 5 dB flatness of the spectral intensity, achieved with 8.3 μJ pump pulses, was maintained in the wavelength interval from 2 to 5 μm (a span of 3000 nm). The main limitation of further spectrum extension was the damage to the InF₃ fiber at higher pump pulse energies; the damage threshold was experimentally determined to be ~200 GW/cm².

Similar to the case of ultrashort (femtosecond) pump lasers, the average output power generated from OPGs is generally at the mW level. A simpler boosting method is to employ a power amplifier. This approach was tested by Gauthier et al. who developed a 2.4–5.4 μm SC source based on a fluoroindate fiber pumped by an Er³⁺:ZrF₄ fiber amplifier, seeded with 400 ps pulses at 2.75 μm [58,104]. The setup and output-measured spectra are shown in Figure 7.
The setup consisted of (1) a 2.75 μm OPG providing a 400-ps pulse train with an average output power of 2 mW generated at a pulse repetition frequency (PRF) of 2 kHz, (2) an erbium-doped fluoride fiber amplifier pumped by a 970-nm laser diode, and (3) a low-loss fluorindate fiber that was fusion-spliced to the fluoride amplifier. The amplifier was made of a 1.25-m-long Er\(^{3+}\):ZrF\(_4\) double-clad fiber. The fluoride amplifier end was subsequently spliced directly into an InF\(_3\) fiber with a core diameter of 11–12 μm or 12.5–14.5 μm. The attenuation was significantly low, equaling 30 dB/km for all wavelengths between 2.2 and 4.2 μm, with a minimum value of 12 dB/km at 3.8 μm.

The amplified signal generated at the maximum available pump power was broadened to ~3.2 μm when measured at the noise level. Different lengths of InF\(_3\) fiber were tested during the course of the experiment. The broadest spectrum was recorded for the 15-m-long fluoride fiber. It spanned more than one octave, from 2.4 to 5.4 μm (~20 dB level), with 82.3% of its energy beyond 3 μm (Figure 7, lower blue curve). As can be seen, for wavelengths longer than 5.2 μm, the steep decrease in the spectral density resulted from the InF\(_3\) fiber transparency limit.

The average output SC power was measured to be 8 mW. The main limitation of the output SC power was the onset of the parasitic lasing threshold of the erbium fiber amplifier that most probably resulted from the slight reflections at the fusion splice. However, to further increase the output power, the research group used the same setup configuration, and the seed OPG was replaced with one operating at ten times higher PRF (20 kHz) and delivering an average output power of 7 mW [104]. The authors also used an InF\(_3\) fiber, 14 m in length, with a core diameter of 12.5–14.5 μm. Therefore, they achieved 145 mW SC power with a spectral width similar to that obtained for the seed operating at 2 kHz (Figure 7, upper red curve). Similar to that in the previous case, the parasitic lasing threshold limited the maximum achievable output power.

It is worth emphasizing that OPG-based SC sources can mainly be used in a laboratory environment. Although OPGs can provide high peak power pump pulses, also with wavelength tuning possibility, they are more complex than classical laser systems (and thus more expensive), require constant maintenance, and are susceptible to environmental conditions (vibrations, air humidity). For this reason, so far, they have found only limited use in commercial products and have not been used for commercial InF\(_3\) fiber-based supercontinuum sources. Therefore, alternative pump schemes have been searched for
and examined over the last years. Examples of such laser systems are described in the following Sections.

5. Mid-Infrared Supercontinuum Generation Using Fiber MOPA Seeded with 1.55 μm Pulses

The SC architectures presented in the previous two Sections exhibited immense potential for broadband mid-IR SC generation in InF₃ fibers; however, owing to the pump laser sources used, the output SC power was limited to milliwatts. To achieve a higher output SC power, more powerful pump sources are required. One successful approach is to use a 1.55-μm nanosecond or sub-nanosecond seed laser in tandem with Er³⁺-doped (or/and Er³⁺:Yb³⁺-doped) fiber amplifiers and Tm³⁺-doped fiber amplifiers (TDFAs) as pump sources [33,59,105]. Such a laser system configuration is commonly known as a master oscillator power amplifier (MOPA) [106–108]. In this approach, seed pulses (of picosecond or nanosecond duration and the desired wavelength) can be delivered by Q-switched/gain-switched oscillators (including fiber lasers) or pulsed semiconductor lasers. The optical pulses are subsequently amplified to the required peak power level in an appropriately designed one-stage or multi-stage fiber amplifier. Finally, the amplified pulses are launched into a nonlinear medium.

This pump setup enables scaling up the average output SC power linearly while maintaining a relatively constant spectral width. This can be achieved by increasing the repetition frequency of the pulses generated by the seed with a simultaneous increase in the average pump power that can be easily realized by providing a suitable gain in the final power amplifier of the MOPA system. Provided that the peak power of the pumping pulses is at the same constant level, the width of the generated SC spectrum should be kept constant. An exemplary setup for SC generation based on a MOPA is shown in Figure 8.

![Figure 8. Schematic of the setup for SC generation based on a MOPA seeded with ~1.55 μm pulses. EDFA: erbium-doped fiber amplifier, EYDFA: erbium:ytterbium-doped fiber amplifier, SMF: single-mode (silica) fiber, TDFA: thulium-doped fiber amplifier.](image)

A train of seed pulses is first pre-amplified in an erbium-doped fiber amplifier (EDFA) and erbium:ytterbium-doped fiber amplifier (EYDFA). Subsequently, resulting from MI and Raman scattering, the pulses propagating in a short piece of single-mode standard silica fiber split into shorter sub-pulses and are red-shifted [109], leading to a spectrum spanning from ~1.4 to 2.4 μm. Finally, the spectral components from the ~1.9 to 2.1 μm range are amplified and undergo further SSFS to longer wavelengths in a single-stage or dual-stage TDFA that acts as a nonlinear and active medium. This mechanism is well-described in refs. [110–112]. The spectral components from ~1.5–1.85 μm are absorbed by the TDF that acts as an isolator, preventing back-reflection-induced damage to the EDFAs and EYDFA, while wavelengths longer than 1.85 μm are amplified and further red-shifted during propagation through the TDF. In the fluoride fiber, the initially broadened pump radiation is extended further into the mid-infrared region, reaching the LWE theoretically determined by material losses.

Note that in this approach, the pump pulse breaks up, forming a series of femtosecond-scale sub-pulses, which, being red-shifted, give rise to light components at a wavelength of ~2 μm. This technique can eliminate the use of high-peak-power mode-locked
Lasers operating in this wavelength region. Additionally, such a laser system is built with the use of widely available active fibers and standard fiber-coupled passive components. This allows for high flexibility in construction and reduction of development costs while providing good optical parameters for the generated pump pulse train. Based on this concept, multi-Watt-level SC generation with a spectrum extended over 5 μm was demonstrated. The most interesting results are discussed below.

The first report on this concept was presented in 2006 [113], but the first practical implementation using InF₃ fibers was conducted by Theberge et al. in 2018 [59]. The pump source consisted of a 1.55-μm distributed feedback (DFB) fiber-pigtailed laser (50 ps, 1 MHz), a double-clad EDFA pumped at 980 nm, and two TDFAs, of which the first was core-pumped by the EDFA and the second was cladding-pumped at 791 nm. The amplified and initially broadened signal with an output power of 2.3 W was subsequently launched using butt-coupling into a 20-m-long InF₃ fiber (core diameter of 9.5 μm, clad diameter of 100 μm, NA of 0.3, ZDW of 1.9 μm, cut-off wavelength of 3.7 μm). After optimization, the authors demonstrated the generation of 1-W SC spanning over 2.25 octaves, from 1 to 5 μm (Figure 9a). The SC spectrum exhibited high spectral flatness with a 6-dB spectral bandwidth from 1.91 to 4.77 μm.

![Figure 9. SC spectra generated from fluoroindate fibers, recorded for different average output powers: 1 W (a), 1.35 and 4.06 W (b), 2.95 W (c), and 11.8 W (d). Corresponding pulse repetition frequencies are shown in parentheses. (a) Reproduced with permission from [59]. Copyright 2018, Chinese Laser Press. (b) Adopted with permission from [60], Copyright 2018, Optica Publishing Group. (c) Reproduced from [77]. (d) Reproduced under the terms of the Creative Commons BY license [61].](image-url)
Using a MOPA seeded by a 1550-nm laser diode as a pump source enables the linear scaling up of the average SC output power, as stated above. This can be achieved simply by increasing the repetition frequency of the pulses generated by the seed. Such SC power scaling has been demonstrated by Yang et al. [60]. The pump laser system involved a 1.55-μm seed laser, a dual-stage EYDFA, a 10-m-long single-mode passive silica fiber (SMF-28e), and a single-mode TDFA followed by a mode field adapter (MFA). The DFB laser was electrically modulated and emitted a train of 1.6-ns pulses with a variable PRF of 100–1000 kHz. The pump laser system generated an average power of 2.27 and 6.41 W for PRFs of 100 and 1 MHz, respectively. The output signal spectrum covered a spectral range of approximately 2–2.7 μm. The output pigtail of the MFA was fusion-spliced with a 10-m-long InF₃ fiber with a core diameter of 7.5 μm and an NA of 0.3. The fusion splicing loss was determined to be 0.07 dB; thus, it provided an extremely high coupling efficiency, minimizing the heat accumulation at the pump-end of the fluoride fiber. Moreover, to reduce the power intensity at the end facet of the InF₃ fiber and improve the power handling performance of the SC source, an endcap made of a piece of multimode ZBLAN fiber of ~200 μm in length was spliced.

By gradually increasing the pump power, the SC spectrum becomes increasingly flatter with the simultaneous extension of the LWE. For a maximal output power of 1.35 W (PRF of 100 kHz), the LWE reached 5.2 μm, and a 1.5-dB spectral flatness was maintained in the range of 2.48–4.75 μm. The power conversion efficiency was determined to be 59.5%. When the PRF was 1 MHz, an SC power of 4.06 W (power conversion efficiency of 63.3%) and a spectrum that extended to 5.1 μm were demonstrated (Figure 9b). The developed SC source was also characterized by high output power stability with a normalized root mean square (RMS) of 0.37%, determined when the source generated an output power of 4 W at a PRF of 1 MHz. Furthermore, no power degradation was observed in the experimental study.

The spectrum spanning the entire 2–5 μm wavelength band with Watt-level output power was also demonstrated by Swiderski et al. [77]. The pump scheme was similar to that described above, except that the pump light was lens-coupled to the fluoride fiber. In this arrangement, 900 ps pulses at a wavelength of 1.55 μm and a repetition frequency of 500 kHz, provided by a 4-GHz DFB laser, were amplified in a cascade of two EDFAs and an EYDFA providing over 2.1 W of average output power. Subsequently, the light propagating in a short piece of single-mode standard silica fiber was red-shifted, leading to a spectrum spanning from ~1.4 to 2.4 μm. Finally, it was amplified and further red-shifted in a single-stage TDFA, reaching a maximum average output power of 6.15 W and a spectrum spreading from ~1.9 to 2.7 μm. Owing to the precise optimization of the laser system, this approach led to efficient power distribution for wavelengths longer than 2.4 μm. For wavelengths longer than 2, 2.4, and 2.5 μm, powers of 5.09 (82.8% of the total output power), 2.02 (32.9% of the total output power), and 1.2 W (19.5% of the total output power) were measured, respectively. The radiation generated at the TDFA output was injected into a 12-m-long step-index InF₃ fiber (core/clad diameter of 7.5/125 μm, NA of 0.3) by a telescope formed by two antireflection-coated lenses, allowing for a launch efficiency of ~75%. Increasing the TDFA pump power corresponds to an increase in the output mid-infrared SC power, whereas the LWE of the output spectrum extends gradually toward the deep infrared wavelengths. After reaching an output power of 2.95 W, the spectrum spanned from ~1.90 to 5.13 μm (Figure 9c). The dips at ~2.8 and ~4.3 μm correspond to OH⁻ ions and the absorption of atmospheric CO₂ in the detection system, respectively. A spectrum flatness of 10 dB was demonstrated in the 1.96–4.97 μm wavelength range. SC evolution was not examined at shorter wavelengths (<1.9 μm) because of the limitations of the detection system used. Further, power upscaling was limited by the available pump power.

A consecutive SC power increase was demonstrated by Yang et al. [61]. Similar to the previous three cases, the SC source comprised a 1.55-μm seed laser (PRF of 1–3 MHz, pulse duration of 1 ns), an amplification and frequency-shift module (EYDFA, SMF-28,
and TDFA) with an output spectrum spanning the region of 1.9–2.6 μm, a single-mode passive fiber, and an InF₃ fiber. The 11-m-long fluoride fiber featured a core diameter of 7.5 μm, core NA of 0.3, and cut-off wavelength of 2.9 μm. The output of the TDFA was first spliced into a short piece of passive single-mode silica fiber (functioning as a bridge between the TDF and fluoride fiber), and subsequently, the SMF was fusion-spliced into the InF₃ fiber. Furthermore, to protect the fiber end from photodegradation during high-power operation, an endcap made of multimode AlF₃ fiber was fabricated.

The SC source was tested for both PRFs. At 3 MHz and a pump power of 17.5 W, the output power was 11.7 W, and the corresponding spectrum extended into the mid-infrared region with a cut-off wavelength at 4.6 μm. Further power scaling up was possible, but it was not applied because the authors intended to avoid probable endcap damage under high-power operation. The power above 2.4 and 3.8 μm was 7.26 (62.1% of the total output power) and 0.75 W (6.4% of the total output power), respectively. It was also noticed that the efficiency of power distribution toward the mid-infrared region (above 3.8 μm) was limited by the inefficient peak power of the pump pulses. Therefore, in the following part of the study, the PRF was lowered to 1.5 MHz, and the maximum pump power was 18.3 W. As a result, an SC with a spectral coverage of 1.9–4.9 μm and a maximal average power of 11.8 W was demonstrated (Figure 9d). The power conversion efficiency toward red wavelengths also significantly increased. A power of 2.18 W (18.5% of the total power) was measured in the spectral region beyond 3.8 μm. The authors emphasized that a power ratio beyond 3.8 μm could be further improved by lowering the PRF.

6. Mid-Infrared Supercontinuum Generation Using Fiber MOPA Seeded with 2 μm Pulses

Broadband and high spectral flatness SC generation can also be achieved by using ps-scale optical pulses with a central wavelength of ~2 μm. Recently, semiconductor fiber-pigtailed lasers operating at approximately 2 μm have become available that have paved the way for the development of fiber-based MOPA systems. InF₃ fibers exhibit favorable dispersion properties for SC generation when pumped at this wavelength; thus, these pump sources are extremely useful for efficient SC generation.

This configuration of the pump laser system was successfully used for SC generation by Liang et al. [114], who demonstrated a 2.5-octave SC spectrum, extending up to 5 μm, generated by an InF₃ fiber. The MOPA system was composed of a 1953-nm discrete-mode laser diode gain-switched at a PRF of 1 MHz, delivering pulses with a duration of ~100 ps. First, the pump pulses were pre-amplified in two TDFAs core-pumped by 1.56 μm fiber lasers. The next two fiber amplifiers were developed using a double-clad fiber (core/clad diameter of 11/127 μm and 25/250 μm), cladding-pumped at a wavelength of 790 nm. A detailed description of MOPA optimization is presented in [114]. An average output power of 10.34 W and a pulse width of 35 ps were detected at the end of the final TDF. The maximum pulse energy and corresponding pulse peak power were estimated to be 10.34 μJ and 295 kW, respectively. It was also noticed that the optical pulse was compressed along the fiber amplifier chain (from ~100 to 35 ps) that resulted from the interplay between the dispersion and SPM. This radiation, applying free-space coupling, was launched into a commercially available 10-m-long fluoroindate fiber with a core/cladding diameter of 9/125 μm and core NA of 0.26 (Thorlabs [94]). At the maximum pump power, the total average SC output power was measured to be 1.76 W and the spectrum extended from ~1 to over 5 μm (Figure 10).
The power for wavelengths longer than 2.9 and 3.5 μm was determined to be 0.56 (32% of the total output power) and 0.33 W (19% of the total output power), respectively. Furthermore, the authors demonstrated remarkable spectrum flatness. The spectrum was maintained with spectral fluctuation within 3 dB over a span of 1870 nm, from 2.5 to 4.37 μm.

A 2-μm laser diode can be replaced by another pulsed laser source operating in this wavelength region, such as a mode-locked fiber laser, as reported by Wu et al. [42]. In the experiment, the authors demonstrated 10-W-level SC generation in the InF₃ fiber. The MOPA was seeded with a 1956-nm SESAM mode-locked fiber laser delivering 60 ps pulses at a PRF of 33 MHz with an average output power of 10 mW. Two fiber amplifiers were used to amplify the pulses. The average power of the pump pulse train was boosted by the first TDFA to 1.65 W and by the second amplifier to 17 W under the maximal available pump power. The output of the final TDFA was spliced to a 7-μm core (NA of 0.2) mode-field adaptor, allowing easy pump-radiation launching into the fluoride fiber. The InF₃ fiber featured a core diameter of 7.5 μm, NA of 0.3, and length of 11 m. The geometrical parameters of the fluoroindate and silica (MFA) fibers permitted efficient fusion splicing with a splicing loss of 0.12 dB. The output end of the InF₃ fiber was also terminated with a short piece of AlF₃ fiber that improved the fiber performance during operation at high powers.

The output SC spectrum, at the maximum pump power, spanned the wavelengths of 0.78–4.7 μm, and the maximum average output SC power was 11.3 W (Figure 11a,b). Additionally, a 20-dB spectral flatness was maintained in the wavelength range of 1.85–4.53 μm without considering the residual pump peak at 1.95 μm. The power conversion efficiency, determined to be 66.5%, was also remarkable. The authors calculated that only 3.3% of the SC power was contained in the spectral range of 1.94–1.97 μm, corresponding to the residual pump peak.
The developed SC source was characterized by high output power stability, as illustrated in Figure 11c. For a short-duration test (12 min) at a power of 10.17 W, the normalized RMS of the SC power was 0.33%. Similar to the other cases, the spectrum LWE was restricted by the background loss of the fluoride fiber. It is also worth emphasizing that no photodegradation or temperature rise of the fusion splicing joint or fiber tip was observed during the experiment, which is of immense importance for practical applications.

7. Mid-Infrared Supercontinuum Generation Using 2 μm Pulses Emitted by Q-Switched/Gain-Switched and Mode-Locked Laser Systems

High-power SCs can be generated using optical pulses on the picosecond or nanosecond scale, as stated in the Introduction. Q-switching of the fiber laser cavity [115–117] can simply lead to the emission of pulses with widths usually from several to tens of nanoseconds and repetition rates from tens to hundreds of kilohertz. Unfortunately, owing to their long duration, their peak powers are not considerably high; consequently, they are not suitable for broadband SC generation. Another method of pulse generation is mode-locking (ML), which can provide highly repetitive pulses with picosecond or sub-picosecond durations [37,118,119]. However, the average output power generated directly from single ML oscillators is also low; for high-power applications, it has to be boosted using power amplifiers that make the system complex, particularly if the chirped-pulse amplification (CPA) technique [120] is applied.

A solution for the generation of short-kilowatt-level pulses is the simultaneous use of Q-switching and active mode-locking (QS-ML) techniques [121]. As a result, a series of ML sub-pulses, spaced exactly by the cavity round-trip time, are recorded within one Q-switch pulse envelope. The advantage of this method is the reduced complexity of the entire SC source owing to the single-oscillator approach. Based on this concept, the SC power of 7 W with a mid-IR spectrum cut at 4.7 μm has been demonstrated [122]. The experimental setup of the pulsed Tm-doped fiber laser used in this experiment and the setups adopted to generate SC radiation are shown in Figure 12a,b, respectively.
The laser resonator was formed by a tunable volume Bragg grating on one side, an active fiber, and an output coupler mirror on the other side. A 2.2-m-long double-clad TDF with a diameter core of 25 μm (0.08 NA) was used as an active medium. It was pumped from both ends by two 792-nm laser diodes, each delivering a maximum output power of 150 W. In addition, two endcaps were fusion-spliced onto the tips of the active fiber to reduce the power density and, eventually, minimize the risk of thermal damage. Two free-space acousto-optic modulators (AOMs) that provide active ML and QS were used inside the cavity. The optical beam generated by the oscillator was first attenuated and subsequently coupled into a 15-m-long InF₃ fiber with a core diameter of 7.5 μm (NA of 0.3). To provide stable and reliable air-to-fiber coupling, an intermediate 1-m-long and 26-μm-diameter core single-mode ZBLAN fiber was used. Radiation from the fluorozirconate fiber was launched into the InF₃ fiber using two commercially available collimators.

In the QS-ML regime, the fiber oscillator could generate a maximum average output power of 40 W at a Q-switch repetition rate of 150 kHz. However, for experiments with SC generation, an average output power of 15 W at a pulse repetition rate of 60 kHz was used. Simultaneous QS-ML provided a macro-QS pulse width of ~90 ns with ~10 ML sub-pulses recorded within one Q-switch pulse envelope, exactly spaced by 37.9 MHz, corresponding to the cavity round-trip time. The ML pulse width was ~30 ps, and the most energetic QS-ML pulse featured an energy of 88 μJ and an estimated peak power of 60 kW.

For the highest launched average pump power (10 W), an SC spectrum with a total output power of 7 W and an LWE at a wavelength of 4.7 μm was obtained (Figure 12c). Although the spectrum was not extremely flat, as expected, this is the first experimental demonstration of high-power SC generation in an InF₃ fiber pumped using a single-oscillator laser system. A possible reason for the lower spectral distribution in the mid-IR region is that the output spectrum is a superposition of different spectra generated by individual ML sub-pulses having different peak powers depending on the position in the QS envelope. A drawback of this source is that the pump fiber laser does not provide a compact all-fiber setup that is preferred in many applications.

An alternative approach permitting high SC power distribution over a wide spectral range was proposed in ref. [123], where a resonantly pumped fast gain-switched (GS) and simultaneously mode-locked Tm-doped fiber laser and amplifier system was used to
pump a fluoride fiber. In the gain-switching technique of a laser resonator, pulse operation is performed by an active medium gain on/off switching via pump-power modulation. In particular, a fast GS, along with resonant pumping, can provide stable 2-μm pulses of short duration (<100 ns). In-band pumping ensures rapid population inversion that can be depleted by a single short-gain-switched pulse. Subsequently, the cross-relaxation and excited-state absorption processes can be reduced, leading to the generation of a stable, short 2-μm pulse train [124]. Combining GS and ML can lead to the generation of a stable train of regular ML sub-pulses of the same width recorded within one GS pulse envelope [125]. The schematic of the setup of this pump source, including the setup for SC generation, is shown in Figure 13a.

![Figure 13](image)

**Figure 13.** Experimental setup of SC generation (a). In order: semiconductor saturable absorber mirror (SESAM), fiber Bragg grating (FBG), wavelength division multiplexer (WDM), MOPA–Master Oscillator Power Amplifier, Er3+:Yb3+-doped fiber ring laser (EYDFL), laser diode (LD), Tm3+-doped fiber (TDF), pump and signal combiner (PSC), lenses (L1–L4), optical isolator (ISO), and dichroic mirror (DM). SC spectrum generated at the output power of 1.14 W (b). Adopted with permission from [123]. Copyright 2021, Optica Publishing Group.

The oscillator was arranged in the linear cavity formed by a fiber Bragg grating (FBG) centered at 2000.1 nm on one side, a 30-cm-long single-mode gain TDF, in-core pumped by a 1.55-μm MOPA, and SESAM on the other side. The 1.55-μm MOPA delivered 100 ns pulses with a repetition rate of 50 kHz, thus providing in-band pumping and fast gain switching of the thulium oscillator. Mode-locking was performed using a commercially available SESAM (BATOP GmbH). It provided stable GS-ML pulses with a repetition rate of 50 kHz and an average output power of ~20 mW. The GS pulse envelope had a full width at a half maximum (FWHM) of ~120 ns. The repetition rate of the 100% modulated ML sub-pulses present within the GS pulse envelope was 111 MHz, consistent with the cavity round-trip time. The seed laser was operated at a central wavelength of 2000 nm.
with a 3-dB bandwidth of 0.2 nm. In the next step, to increase the peak power of the generated pulses, the radiation was amplified in two TDFAs. The first T DFA delivered an average output power of ~120 mW, with most of the pulse energy located in the spectral peak at ~2 μm. The second T DFA provided a maximum average output power of 2.45 W at a launched 790-nm pump power of 7 W. The output spectrum was moderately broadened compared to that of the oscillator, primarily owing to modulation instability and Raman scattering in the T DFA [30]. It spanned from ~1.88 to 2.34 μm; however, most of the power corresponded to wavelengths of approximately 2 μm. More details of the laser system can be found in ref. [125].

Finally, the amplified 2-μm pulse train was injected into an 11-m-long step-index InF₃ fiber with a core/clad diameter of 7.5/125 μm and an NA of 0.3. As the launched average pump power was increased to 1.85 W, the average output SC power reached 1.14 W, and the corresponding optical-to-optical conversion efficiency was measured to be 61.6%. The output spectrum spanned from 1.9 to 4.75 μm at the noise level (Figure 13b). Owing to the limitations of the detection system, the short-wavelength region of the spectrum was not investigated. Furthermore, the spectrum measured for the maximum output power was predominantly flat, except for the dips around ~2.8 and 4.3 μm corresponding to the absorption of OH⁻ ions and atmospheric CO₂, respectively, during the free-space light propagation through the detection system. More specifically, the spectral bandwidth of 10 dB for the maximum output power, excluding the residual pump peak around a wavelength of 2 μm, was 2500 nm, and the corresponding spectral range was from 1.94 to 4.44 μm. Furthermore, the spectral integral shows that 88% and 30% of the output SC power are converted for wavelengths beyond 2.15 and 3.5 μm, respectively. The presented GS-ML fiber laser system is relatively easy to develop, particularly because it is based on commercially available off-the-shelf components. The number of free-space optics was reduced to the minimum; therefore, the system was less susceptible to atmospheric conditions, such as dust and vibrations. It is believed that by applying a more powerful pump source and optimizing the InF₃ fiber length, it is possible to extend the spectrum further into the mid-IR region while maintaining suitable spectral flatness.

8. Summary and Outlook

Mid-infrared supercontinuum sources have developed rapidly in the last 15 years. The emergence of specialty glass fibers, such as fluoroindate fibers, as well as the advances in fiber-based pulsed oscillators and amplifiers, have accelerated the development of high-power SC systems operating in the spectral range of 2–5 μm. In addition to the output power, the spectral width and flatness of the continuum are important parameters that determine the SC source performance and its usefulness. The first demonstration of SC generation in a fluoroindate fiber was reported by Theberge in 2013 [101]. Since then, much effort has been devoted to improving all the key output parameters of such sources. In less than a decade, the output SC power has been scaled up by more than three orders of magnitude (from less than 10 mW to more than 11 W). Furthermore, interesting pump schemes that enable watt-level SC generation have been proposed. The main achievements in this field are summarized in the chart shown in Figure 14, which illustrates the average SC output power increase over the past nine years. Additionally, Table 1 presents a summary of the most important results on SC generation using InF₃ fibers, as well as the basic information about the parameters of pump radiation and pump laser system configurations.

As can be seen in Figure 14, remarkable progress has been made in scaling up the output SC power (illustrated by the increased number of reports as well as increasingly higher output powers), particularly during the last four years. A record time-averaged output power of 11.8 W with a spectrum spanning from ~1.9 to 4.9 μm has been demonstrated, which is certainly not the power limit of this technology. This can be scaled up further if improved thermal management and heat dissipation techniques are implemented. Another vital parameter of mid-IR SC generation is the power distribution
toward the red wavelengths. Using optimized nonlinear InF₃ fibers and applying suitable pump sources, it was possible to demonstrate an LWE of 5.42 μm for low-power systems (an output power of 8 mW) and 5.1 μm for high-power operation (an output power of 4.06 W). Furthermore, an excellent spectral flatness (5 dB@ 2.0–5.0 μm and 10 dB@ 1.96–4.97 μm) was also achieved. This progress cannot occur without suitable pump sources, particularly those allowing output SC power scaling up. In addition to conventional femtosecond ML laser systems, including optical parametric generation techniques, a spectrum of interesting laser system solutions that provide picosecond and nanosecond pulses has been proposed. It includes fiber-based MOPA systems seeded with semiconductor lasers operating at wavelengths of 1.55 and 2 μm, Q-switched and ML fiber single oscillators, 2-μm fast gain-switched and simultaneous ML fiber lasers and amplifiers, and fiber amplifiers directly seeded with picosecond ML lasers. Regarding nonlinear InF₃ fibers, most reports have focused on fibers with a length of 8–15 m and a core diameter of 7–10 μm. The fibers with the lowest attenuation and an appropriate profile of the dispersion curve supported the most efficient red-shifting of the generated SC with an LWE of up to 5.42 μm. There is scope for further spectrum extension, but it would be rather difficult because of the high absorption losses over 5 μm resulting from the multiphonon absorption edge of fluoroindate glasses.

![Figure 14](image)

**Figure 14.** Summary of the most important reports on SC generation (with an LWE of output spectrum beyond 4 μm) in fluoroindate fibers published in the last decade. The bandwidth in the diagram represents the full spectral range (*average output power not revealed; it is supposed to be <100 mW).*

All the pump laser systems summarized in Table 1 have their advantages and disadvantages. For instance, optical parametric oscillators and amplifiers can generate high peak power pulses with the possibility of output wavelength tuning; however, they can only be used for low average power SC generation, mainly in laboratory rooms. Single-pump oscillators, for instance, the Q-switched and mode-locked fiber lasers [122], can support watt-level SC generation, providing the SC system simplicity and cost reduction, but in this case, the pump pulse structure has high amplitude fluctuations affecting the stability of the output SC power. MOPAs seeded with ~1.55 or ~2 μm nanosecond and
sub-nanosecond optical pulses [59–61,77,114], especially the all-fiber ones, can offer pump beams with high average power, being perfectly suited for high-power SC systems. Furthermore, they can generate optical pulses with adjustable durations and repetition frequencies independently. It allows changing the peak power of pumping pulses (time-averaged pump power) in the same laser configuration. They are much more complex compared to single oscillators, mainly due to the number of fiber amplifiers needed to provide the optical pump beam with the required power level. On the other hand, they can be fusion spliced with a nonlinear fluoride fiber, making the whole SC system all fiber, which is favorable in the context of practical applications where output parameters stability over a longer operation term is required. Furthermore, this approach enables scaling up the average output SC power linearly while maintaining a relatively constant spectral width of the output spectrum.

Although significant progress has been realized, higher output powers, improved spectral characteristics (higher bandwidth and enhanced flatness), and higher reliability of the entire SC system can be achieved further. However, some issues still need to be considered to achieve this aim. First, the development of the first SC sources utilizing InF3 fibers was hindered by the poor quality of the nonlinear medium that hindered the generation of high output SC powers. Thermal effects and the optical damage threshold, defined by a low transition temperature, were the main factors limiting the output power. Over the last few years, the quality of InF3 fibers has significantly improved, and it can be assumed that further improvements pertaining to enhanced optical and mechanical properties are expected. In particular, fibers without absorbing centers are required. Second, further advances in pump laser systems and techniques for launching pump radiation into a nonlinear fiber are required. Further investigation remains to be conducted to achieve robust and compact high-power mid-IR SC sources for practical use. Ensuring the wall plug efficiency of the entire SC laser system is problematic. It was shown that for the scaling up of power, pulsed fiber-based multi-stage MOPA systems are usually utilized, and the more complex the system, the lower is its total power conversion efficiency. In this context, pulsed laser systems developed as single oscillators or MOPAs with a reduced and optimized number of amplifiers should be used. Furthermore, to improve SC system reliability and ruggedness, it should be developed in an all-fiber format that is feasible. The recent reports show that attenuation at the splice point of silica and fluoroindate single-mode fibers can be as low as 0.03 dB (measured at a wavelength of 2 μm [42]). Another approach to avoid system failure is to protect an InF3 fiber end face from photodegradation, and the power intensity at the output end is to splice a multimode AlF3 fiber endcap [42,126]. These modifications should improve the performance of high-power SC sources and decrease the system complexity. Third, the output power stability of SC sources is also an important parameter that defines true potential toward real-world practical applications. Unfortunately, this issue was not investigated in most of the reviewed papers. Nevertheless, some conclusions seem to be obvious. Low-power mid-IR SC sources, pumped by OPGs, have rather low output power stability, which directly results from the poor stability of pumping pulses. The power stability of high-power InF3-based SC sources is determined by the power stability of fiber-based pump laser systems. The Q-switched Tm-doped fiber lasers [122] and gain-switched Tm-doped fiber lasers and amplifiers [123] provide output pulses with quite high fluctuations of amplitude, and consequently, it can be assumed that the output SC power is not very stable. The fiber-based MOPAs seeded with semiconductor lasers, or mode-locked fiber lasers seem to provide better power stability over a long period of operation. In particular, all-fiber systems, where the output of the pump MOPA system is fusion spliced to a fluoroindate fiber, can improve the thermal management, conversion efficiency, and can offer an excellent SC source operation. Recently, Wu et al. reported an SC laser system tested for over 12 min at an output power of 10.17 W, showing a highly stable output beam with RMS of the SC power of 0.33% [42]. Based on the presented results, this concept seems to be the best for practical applications. Fourth, further improvements in the performance of SC sources
should pave the way for new applications in both academia and the industry (e.g., spectroscopy and medicine).

Table 1. Summary of key results of and setups for SC generation in fluorindate fibers (OPG—optical parametric generator; MOPA—master oscillator power amplifier; DFB—distributed feedback; EDFA—erbium-doped fiber amplifier; EYDFA—erbium:ytterbium-doped fiber amplifier; TDFA—thulium-doped fiber amplifier; MLFL—mode-locked fiber laser; DM—discrete mode; QML—Q-switched and mode-locked; GSML—gain-switched and mode-locked; PRF—pulse repetition frequency; LWE—long-wavelength edge; INP—information not provided).

| Pump Source Architecture | pump Parameters (Pulse Width/PRF/ Wavelength/Average Power) | InF3 Fiber Parameters (Core Diameter/NA/Fiber Length) | SC Parameters (Average Power/LWE/ Spectral Flatness) | Ref. |
|--------------------------|--------------------------------------------------|-------------------------------------------------|-----------------------------------------------|-----|
| OPG                      | 70 fs/INP/ 3.4 μm/INP                             | 16 μm/0.14/9.5 m                                | INP/4.95 μm/ 20 dB@2.7–4.7 μm                | [101] |
| MOPA: MLFL (seed), 1xEYDFA, 1xTDFA | 97.5 fs/50 MHz/ 1.55 μm/0.57 W | 7 μm/0.26/0.55 m                                | 247 mW/~5 μm/ INP                            | [102] |
| MOPA: OPG (seed), Er3+:ZrF4 amplifier | 400 ps/2 kHz/ 2.75 μm/INP | 13.5 μm/0.3/15 m                                | 8 mW/5.42 μm/ 20 dB@ 2.4–5.4 μm              | [104] |
| OPG                      | 70 ps/1 kHz/ 2.02 μm/INP                          | 9 μm/0.26/9 m                                  | INP/5.25 μm/ 5 dB@ 2.0–5.0 μm                | [103] |
| MOPA: OPG (seed), Er3+:ZrF4 amplifier | 400 ps/20 kHz/ 2.8 μm/INP | 13.5 μm/0.3/14 m                                | 145 mW/~5.4 μm/ 20 dB@ 2.77–5.30 μm         | [58]  |
| MOPA: DFB laser (seed), 1xEYDFA, 1xTDFA | 50 ps/1 MHz/ 1.55 μm/2.3 W | 9.5 μm/0.3/20 m                                 | 1 W/~5 μm/ 6 dB@ 1.91–4.77 μm               | [59]  |
| MOPA: DFB laser (seed), 2xEYDFA, 2xTDFA | 1 ns/5 MHz/ 1.55 μm/3.7 W | 9 μm/0.3/12 m                                  | 1.41 W/4.1 μm/ 10 dB@ 1.91–3.59 μm          | [127] |
| MOPA: DM laser diode (seed), 3xTDFA | 35 ps/1 MHz/ 1.95 μm/INP | 9 μm/0.26/10 m                                 | 1.76 W/5.2 μm/ 3 dB@ 2.5–4.37 μm            | [114] |
| MOPA: DFB laser (seed), 1xEYDFA, 2xTDFA | 50 ps/1 MHz/ 1.55 μm/2.03 W | 9.5 μm/0.3/12.7 m                               | 0.88 W/4.7 μm/ 10 dB@ 1.9–4.4 μm            | [128] |
| MOPA: DFB laser (seed), 1xEYDFA, 1xTDFA | 50 ps/1 kHz/ 1.55 μm/2.27 W | 7.5 μm/0.3/10 m                                 | 1.35 W/5.2 μm/ 10 dB@ 2.02–4.91 μm          | [60]  |
| MOPA: DFB laser (seed), 2xEYDFA, 1xTDFA | 1.6 ns/1 MHz/ 1.55 μm/6.41 W | 7.5 μm/0.3/10 m                                 | 4.06 W/5.1 μm/ 10 dB@ 2.09–4.65 μm          | [60]  |
| MOPA: MLFL (seed), 2xTDFA | 60 ps/33 MHz/ 1.95 μm/17 W | 7.5 μm/0.3/11 m                                 | 11.3 W/4.7 μm/ 20 dB@ 1.85–4.53 μm          | [42]  |
| QML fiber laser (single oscillator) | QS: 90 ns/60 kHz/~2 μm/10 W ML: 30 ps/37.9 MHz | 7.5 μm/0.3/15 m                                 | 7 W/4.7 μm/INP (LWE@10 dB: 3.1 μm)          | [122] |
| MOPA: DFB laser (seed), 1xEYDFA, 1xTDFA | 1 ns/1.5 MHz/ 1.55 μm/18.3 W | 7.5 μm/0.3/11 m                                 | 11.8 W/4.9 μm/ 10 dB@ 2.05–4.60 μm          | [61]  |
| MOPA: DFB laser (seed), 2xEYDFA, 1xEYDFA, 1xTDFA | 0.9 ns/0.5 MHz/ 1.55 μm/~4.5 W | 7.5 μm/0.3/12 m                                 | 2.95 W/5.13 μm/ 10 dB@ 1.96–4.97 μm         | [77]  |
| MOPA: GSML fiber laser (seed), 2xTDFA | GS: 120 ns/50 kHz/2 μm/1.85 W ML: ~110 ps/111 MHz | 7.5 μm/0.3/11 m                                 | 1.14 W/4.75 μm/ 10 dB@ 1.94–4.44 μm         | [123] |

* excluding the peak at the pump wavelength.

An extensive review of the most promising practical realizations of supercontinuum systems, including the diversity of pump configurations, is presented. It is shown that
different pump system configurations delivering femtosecond, picosecond, and nanosecond optical pulses combined with a low-loss InF fiber can support efficient supercontinuum generation with a spectrum covering the entire 2–5 μm spectral band. High-power SC configurations, of which the most powerful one emits an average output power of 11.8 W, are focused on in this study. The review indicates that the potential of fluorinate fibers has not been fully explored yet, and there is still scope for further improvement in their performance, particularly in high-power SC systems.

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