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Recent development of flat supercontinuum generation in specialty optical fibers

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Supercontinuum (SC) generation has attracted a significant scientific interest in the past decades due to its promising applications covering the fields of metrology, spectroscopy, defense, as well as medical treatments. To date, researchers are devoted to improving the spectral width and flatness of SC generation by using specialty optical fibers. The flatness of the spectrum is of importance because it can improve the accuracy of measurement in practical applications. This paper summarizes the theory of SC, the state of the art of flat SC generation using optical fiber including photonic crystal fibers, soft glass fibers as well as germania-doped fibers, and suggests the future research direction of flat SC light source.

Keywords: specialty optical fibers; flatness; supercontinuum light source; nonlinear optics

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Introduction

Supercontinuum (SC) laser sources exhibiting excellent wide bandwidth and good beam quality have attracted much attention because of their potential applications including spectroscopy, optical coherence tomography, chemical detection, biomedicine, as well as homeland security, etc[1–4]. The common method for SC generation is achieved by a piece of highly nonlinear medium pumped by ultra-short pulses[5]. When the ultra-short laser pulse is transmitted in the nonlinear medium, the spectrum of the pulse will produce spectral broadening under the combination of nonlinear effects and group velocity dispersion, thus forming a SC spectrum[6,7]. Because flat SC sources not only can improve the accuracy of the measurement, but also can lower the difficulty of power equalization[6], the flatness of the SC is critical for many practical applications. In recent years, SC sources have been widely researched in the visible, near-infrared and mid-infrared spectral regions. Especially, the 2–5 μm mid-infrared wave band contains several relatively transparent and low-loss windows in the atmosphere, and the characteristic lines of many important molecules are also distributed in this wave band. Therefore, the flat SC source covering mid-infrared wave is very important in practical applications such as atmospheric remote sensing, infrared imaging, and biological detection[8].

The key technologies for SC sources are the flexible pump sources and effective nonlinear media. Conventional nonlinear media for SC generation include bulk solids, gases and liquid materials[8]. However, high quality SC generation in these media require that the seed sources can produce high-density focused beam with extremely high peak power, because the beams will undergo diffraction effects as they are transmitted in the nonlinear media[7]. The emergence of optical fiber greatly accelerates the development of SC generation. In 1976, the SC generation was achieved by injecting a Q-switched pulse from a dye laser into a 20-m-long fiber[9]. Since the light transmitted in the optical fiber doesn't experience diffraction effect, it can provide a high light intensity output over a long distance and mitigate the requirements for the seed sources[6]. Therefore, optical fiber is widely used as a nonlinear medium for SC generation, especially specialty optical fibers, such as photonic crystal fiber (PCF), soft glass fiber as well as germania doped fiber. The nonlinear effects in these optical fibers that lead to SC generation mainly include self-phase modulation (SPM), modulation instability (MI), four-wave mixing (FWM), stimulated Raman scattering (SRS), and soliton

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self-frequency shift (SSFS) and so on[7].

PCF has a flexible design structure whose dispersion and nonlinear characteristics can be adjusted by selecting suitable materials and structure. The application of PCF is mainly targeted for visible and near-infrared flat SC because of its high intrinsic material loss in longer wavelength. Differently, soft glass fiber has low phonon energy and low transmission loss in the mid-infrared wavelength range. It can be used as a nonlinear medium to extend the long wavelength range of SC to the mid-infrared. In the cases of SC generation in soft glass fiber, continuous wave (CW) light pumping SC has the advantages of higher spectral power density, smoother spectrum, lower intensity noise and shorter coherence length[6], but the efficiency of spectrum broadening of a CW laser beam is much lower. Using CW as the pump source usually requires tens of meters or even hundreds of meters of high nonlinear fibers as the nonlinear medium. It is not a problem for silica fiber, but it is still a technical obstacle for soft glass fiber[10]. Compared with above two kinds of optical fibers, the germania-doped fiber has good mid-infrared transparency and capability to be fused with silica fiber, showing great potential to be a nonlinear medium in short-wave mid-infrared SC generation. Although SC generation has been extensively studied, their performance in terms of spectral flatness and conversion of total energy to mid-infrared energy still needs further optimization[11].

In this paper, the basic theory of supercontinuum generation is briefly introduced. Moreover, the paper reviews the state of the art of flat SC generation using optical fiber including photonic crystal fibers, soft glass fibers as well as germania-doped fibers, and suggests the future research direction of flat SC light source.

Theory of supercontinuum generation in optical fibers

The schematic diagram of SC generation is shown in Fig. 1. The SC generation is mainly determined by the matching ways of the pumping method and fiber parameters, and different matching ways correspond to different broadening mechanisms. The physical mechanisms of SC generation in an optical fiber mainly depend on the relationship among the operating wavelength of the pump source, the pulse width of the pump source, and the zero-dispersion wavelength (ZDW) of the nonlinear fiber[12].

The transmission of an optical pulse along an optical fiber for SC generation is generally analyzed by solving the nonlinear Schrödinger equation (NLSE), as shown in equation (1):

$$\frac{\partial A}{\partial z}=-\frac{\alpha}{2}A-\sum_{n\geq 2}\mathrm{i}^{n-1}\frac{\beta_n}{n!}\frac{\partial^n A}{\partial t^n}+\mathrm{i}\gamma\left(1+\frac{\mathrm{i}}{\omega_0}\frac{\partial}{\partial t}\right)\times\left[A(z,t)\int_{-\infty}^{\infty}R(t')\left|A(z,t-t')\right|^2\mathrm{d}t'\right]\;, \tag{1}$$

where α is the loss coefficient of the fiber, $\beta_n\beta_n$ represents the nth-order dispersion coefficient associated with the Taylor series expansion of the propagation constant $\beta(\omega)$ at ω_0, γ is the nonlinear coefficient of the fiber, and $R(t)$ is the Raman response function. The equation can be solved by the split step Fourier method. It can be seen from equation (1) that SC generation in optical fiber is mainly affected by loss, dispersion and nonlinear coefficient of the optical fiber.

In the anomalous dispersion region of the fiber, when the fiber is pumped by femtosecond pulse, the spectral broadening mainly depends on the soliton effect[10]. When pumping fibers with picosecond or nanosecond pulses, modulation instability (MI) is the main cause of SC generation in the first stage[13]. MI is a precursor to the soliton fission. MI requires anomalous dispersion and manifests itself as a breakup of the CW or long pulsewidth pulse radiation into a train of ultra-short pulses during transmission[14]. In time domain, disintegrates pulse (soliton fission) and stable soliton entities are formed. In the frequency domain, MI broadens the spectrum. As the pulses propagate through the nonlinear fiber, each sub-pulse undergoes further spectral broadening through MI, stimulated Raman scattering as well as Raman soliton self-frequency shift[1]. In the normal dispersion region of the fiber, when the fiber is pumped by femtosecond, the SC generation is mainly controlled by self-phase modulation. For long pulse pumping fibers, stimulated Raman scattering and four-wave mixing dominate the spectral broadening[10]. The pumping in the anomalous dispersion region and the operation wavelength close to the zero-dispersion wavelength of the nonlinear fiber can realize the effective broadening of the supercontinuum spectrum toward longer wavelength[15], but the flatness of the spectrum is poor. While pumping in the normal dispersion region of the fiber, the flatness and coherence of the

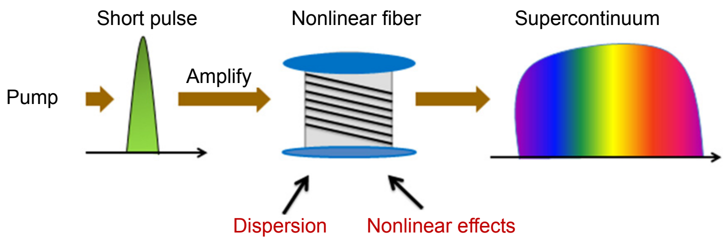

Fig. 1 | Schematic diagram of supercontinuum generation.

spectrum will be better[6].

Supercontinuum generation in specialty optical fibers

For SC generation, optical fiber generally needs both high nonlinear coefficient and appropriate dispersion curve to meet the phase matching conditions required for nonlinear effects[7]. Figure 2 shows the transmission spectra of silica fiber, germania-core fiber, germania fiber and ZBLAN fiber. Beyond 2.4 μm, the silica fibers show high material loss. Compared with silica fibers, the ZBLAN and germania fibers have relatively low transmission loss in longer wavelength. The standard silica fiber has relatively narrow optical transmission window, low nonlinear coefficient, and limited range of dispersion[7], which greatly hinder the improvement of SC performance. So, the specialty optical fibers with excellent dispersion and nonlinear characteristics have attracted much attention including photonic crystal fibers, soft glass fibers and germania doped fibers.

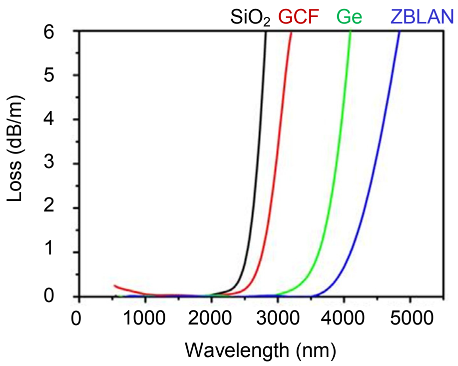

Fig. 2 | Transmission spectra of selected optical fibers (based on the data presented in the available literature). GCF: germania-core fiber; Ge: germania fiber; ZBLAN: ZrF_4-BaF_2-LaF_3-AlF_3-NaF

Supercontinuum generation in photonic crystal fibers

Photonic crystal fiber has a flexible design structure and significant advantages in changing nonlinear coefficients and dispersion. With the development of optical fiber processing technology, multi-core PCF, liquid core filled PCF have appeared. In 2006, A. Kudlinski et al used nanosecond and picosecond pump sources with a working wavelength at 1.06 μm to pump tapered PCFs with a decreasing zero dispersion wavelength along their length. For both pump sources, a supercontinuum with a wavelength range covering 350–1750 nm can be generated, and the flatness of spectrum is less than 10 dB. However, when using a picosecond pulse to pump a 1-m-long PCF, a high spectral flatness of 3 dB was achieved in the wavelength range of 395–850 nm[16]. In 2008, B. A. Cumberland of Imperial College London used a 44 W ytterbium-doped laser to pump a 20-m-long two zero dispersion wavelengths PCF to generate a 29 W supercontinuum, 8-dB bandwidth of the spectrum was 600 nm which spanning 1.06–1.67 μm[17]. In general, continuous wave pumping photonic crystal fibers have higher spectral power densities and smoother spectra than the supercontinuum generated by pulsed beam pumping. In 2010, C. Guo et al of Shenzhen University adopted a continuous wave generated by a 20 W ytterbium-doped laser to pump cascaded PCF and a highly nonlinear fiber. This method utilized the cascaded stimulated Raman scattering effect to increase the conversion efficiency of the residual pump energy to the long wavelength to flatten the spectrum, the 10-dB bandwidth of the spectrum reached 420 nm, and the flatness of the spectrum was 0.7 dB in the range of 1175 nm to 1391 nm[18]. A flat and coherent SC spectrum with uniform high spectral power density is especially important for applications of time resolved measurements. The spectrum with this characteristic is often achieved by using a two ZDWs PCF and dispersion flattened dispersion decreasing PCF, but the usage of two ZDWs PCF as the medium for SC implementation is not advantageous to the generation of broadband SC.

Another way to produce a flat coherent supercontinuum is to use an all-normal dispersion (ANDi) PCF. Such PCF has normal dispersion at all wavelengths covered by SC, and the coherence of SC generated by this method is better and the spectrum is smoother. In 2010, A. M. Heidt et al numerically researched the femtosecond pulse pumping ANDi PCF to generate flat SC in the range of 700–1400 nm, and the average value of flatness variation over the entire bandwidth range was less than ±1 dB[19]. In 2011, A. M. Heidt et al demonstrated the SC generation of near-infrared and visible regions in ANDi PCF through the combination of theory and experiment. The dispersion curve and calculated mode field diameters of the two ANDi PCFs used by the authors are shown in Figs. 3(a) and 3(b), respectively. The maximum dispersion value of PCF A locates at 1020 nm, and that value of PCF B locates at 650 nm. It has been demonstrated by Ref.[19] that the broadest spectrum can be usually obtained when the pumping wavelength is near the maximum value of the fiber dispersion curve. In order to verify this theory, the authors used a 50-fs pulse to pump 0.5-m-long PCF A at 1050 nm and 790 nm, respectively. The spectra obtained are shown in Figs. 4(a) and 4(b). When PCF A was pumped at 1050 nm, the pulse energy increased to 7.8 nJ, the 20-dB spectral width reaches 905 nm with good spectral flatness. However, pumping at 790 nm, when the pulse energy reached 12.5 nJ, the widest spectral width was 880 nm. For more clearly understanding the SC generation dynamics in ANDi PCF A, the authors also simulated the pulse evolution of different transmission lengths, as shown in Figs. 5(a)–5(d), which confirmed that the dominant factors of SC generation in ANDi PCF are SPM and optical wave breaking (OWB). In addition, the authors also conducted

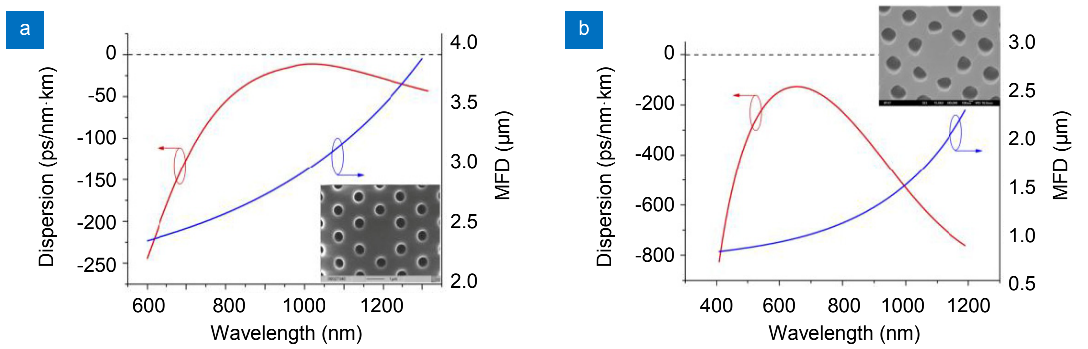

Fig. 3 | Measured dispersion curve and calculated mode field diameter (MFD) for PCF. (**a**) PCF A. (**b**) PCF B. Figure reproduced from ref.[20], Optical Society of America.

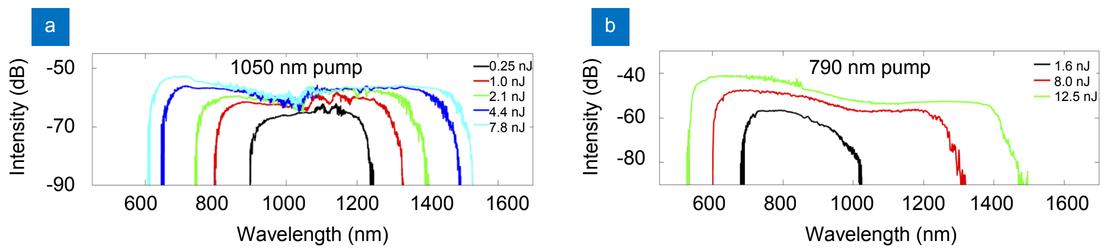

Fig. 4 | Spectra of supercontinuum generation by pumping PCF A in different pulse energy. (**a**) Central pump wavelength at 1050 nm. (**b**) Central pump wavelength at 790 nm. Figure reproduced from ref.[20], Optical Society of America.

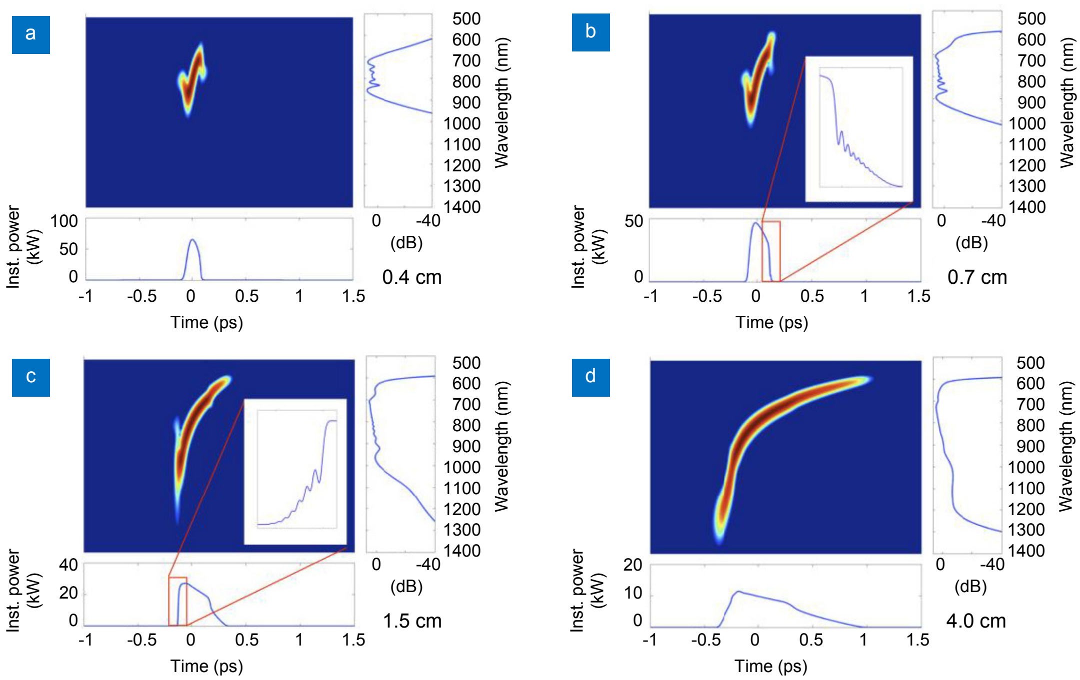

Fig. 5 | Simulated spectrogram of the pulse evolution at different transmission lengths in the ANDi PCF with projected temporal and spectral intensity profiles. Figure reproduced from ref.[20], Optical Society of America.

a series of theoretical and experimental analyses on the visible light SC generated by PCF B[20]. In 2018, C. Huang et al have proposed a hexagonal all-solid-state micro-structured fiber with an ultra-flat, all-normal dispersion curve. In the numerical simulation, a 200-fs pulse pumping the microstructured fiber at 1550 nm was used to achieve an ultra flat spectrum with a flatness fluctuation of less than 3 dB in the wavelength range of 1030 to 2030 nm[21].

Supercontinuum generation in soft glass fibers

In the past decades, the research on SC sources mainly focused on silica fibers because of their stability and low transmission loss in the visible and near-infrared regions.

However, due to multiphoton absorption, silica fibers have high intrinsic material losses above 2.4 μm. The resulting long wavelength edges of supercontinuum is difficult to exceed 2.7 μm, making them no longer suitable for mid-infrared supercontinuum generation[22]. For mid-infrared SC generation, an optical fiber with a longer infrared transmission window is required. Soft glass fibers such as fluoride fibers, chalcogenide fibers, and tellurite fibers have lower phonon energy and lower transmission loss in the mid-infrared region. Among all soft glass fibers, chalcogenide fibers and fluoride fibers are most technically mature and commercially available[23].

The chalcogenide fibers have two orders of magnitude higher nonlinear refractive index than fluoride fibers, and the transmission window can even exceed 20 μm[24]. Most studies based on it are devoted to improving the spectral width of SC. In 2012, R. R. Gattass et al achieved an all-fiber SC source based on As_2S_3 fiber, obtaining a relatively flat SC with wavelength range spanning 1.9 μm to 4.8 μm. The 10-dB spectral width covered 2–4.6 μm[25]. In 2014, C. R. Petersen et al launched ~100 fs pulses with a central wavelength of either 4.5 μm or 6.3 μm into 8.5-cm-long ultra-high numerical aperture chalcogenide-glass SIF, and the generated spectra covered 1.5–11.7 μm and 1.4–13.3 μm, respectively[26]. In 2016, T. Cheng et al used the difference frequency generator as the pump source, and 3-cm-long chalcogenide step-index fiber as the nonlinear medium, which generated SC with the wavelength range covering 2.0–15.1 μm[24]. In 2017, Z. M. Zhao et al demonstrated a SC generation spanning ~2.0 μm to 16 μm, to our knowledge, this is the widest SC which has been generated. The spectrum exhibited the 40-dB spectral flatness over the whole 2.0–16 μm[27].

To date, the widest SC has been generated in chalcogenide fibers, but the zero dispersion wavelengths of chalcogenide fibers usually exceeding 4.5 μm make them difficult to find a suitable and efficient pump source. Compared with chalcogenide fibers, fluoride fibers have higher damage threshold and more stable performance. ZDWs cover the common working range of 1.5 μm to 2.1 μm, making fluoride fibers (especially ZBLAN) be the best candidate for mid-infrared SC generation[15,28]. The supercontinuum generation in ZBLAN fiber was firstly reported by C. L. Hagen et al in 2006. They used a 900 fs pulse produced by a commercial erbium-doped fiber laser to pump cascaded silica fiber and ZBLAN fiber. The output spectral wavelength range from 1.8 μm spanned to 3.4 μm, and the total average power in this range was 5 mW, and the spectral flatness was better[29]. In the same year, it was reported the use of nanosecond pulse to pump ZBLAN fiber to extend the long wavelength edge of mid-infrared SC to more than 4.5 μm[30]. In 2010, G. S. Qin et al used a femtosecond pulse with a peak power of 50 MW to pump 2-cm-long ZBLAN fiber to produce a spectrum extending from 0.35 μm to 6.28 μm, the 10-dB bandwidth of 4861 nm (The spectral range was 565–5246 nm), covering almost the entire fluoride fiber transmission window. So far, the SC above has the longest long-wavelength limit in ZBLAN fibers and good spectral flatness, but it is difficult to achieve high power output. Because the nonlinear fiber length is too short, it is easy to produce overheating[31]. For high-power SC sources, it is usually necessary to use several meters or even tens of meters of fiber to distribute the heat load. However, since the material absorption loss of the ZBLAN fiber rises sharply in the wavelength range of more than 4.5 μm, the long-wavelength limit of the high-power SC is difficult to exceed 4.5 μm. In 2013, NKT used a compact all-fiber structure to broaden the long wavelength edge of high-power mid-infrared SC to 4.75 μm[32], but the flatness of the spectrum still needed to be further improved.

In recent years, the applications of mid-infrared supercontinuum in chemical detection and biological detection have become more and more widespread. The flatness of light sources for accuracy of detection has gradually attracted much attention. In 2017, K. Yin et al used a thulium-doped fiber amplifier to pump a ZBLAN fiber with a length of 12 m, a core diameter of 9 μm, and a numerical aperture of 0.27. A mid-infrared SC source with an all-fiber structure was achieved, the spectral range covered 1.9–4.2 μm and the average output power reached 15.2 W. The source had a flatness of 10 dB from 1960 nm to 4050 nm[3]. In 2018, the researchers have successfully achieved the generation of mid-infrared flat

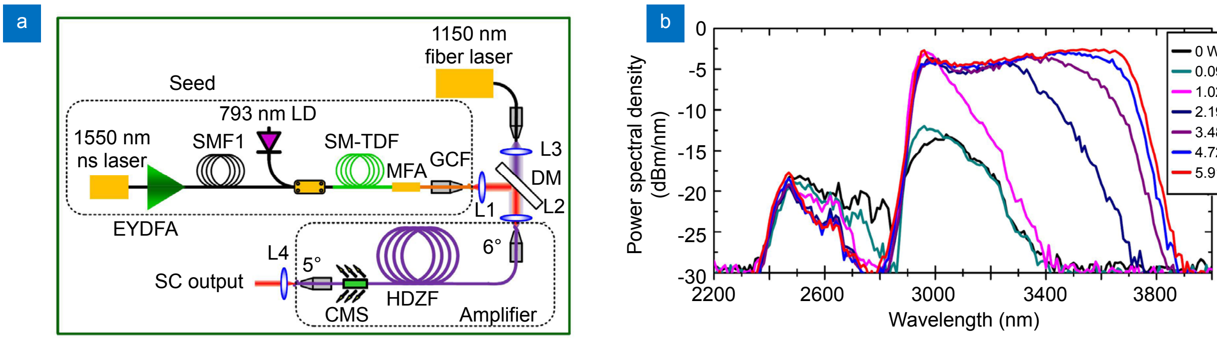

Fig. 6 | Experimental setup and spectra of spectrally flat supercontinuum generation. (**a**) Experimental setup. (**b**) Evolution of SC spectra against launched pump power. Figure reproduced from ref.[4], Chinese Laser Press.

supercontinuum in the holmium-doped ZBLAN fiber amplifier (HDZFA). The experimental setup and the spectrogram are shown in Figs. 6(a) and 6(b), respectively. The whole device was mainly composed of a broadband seed laser spanning the 2.4–3.2 μm region, HDZFA, and the holmium-doped ZBLAN with a length of 4.5 m. The authors studied the variation of SC spectral broadening at the repetition rate of 40 kHz with incident pump power. When the pump power reached 5.91 W, the spectrum spanned 2.8–3.9 μm and the maximum output power was 411 mW. The 3-dB high spectral flatness was achieved in the range of 2.93–3.70 μm[4].

Although ZBLAN fibers have better performance than other fluoride fibers, the existence of their own material absorption loss limits the generation of longer wavelength SC. The advantages of InF_3 fibers over ZBLAN were that their transmission windows can be extended to 5.5 μm. The generation of SC in InF_3 fiber was reported by F. Théberge et al in 2013. A 9.5-m-long InF_3 fiber was pumped by an ultra-short pulse of 73 fs, and a flat SC was achieved with the flatness of 20 dB spanning 2.7–4.7 μm[33]. In 2016, an optical parametric generator (OPG) was used to pump a 9-m-long InF_3 fiber to generate SC. The experimental setup was shown in Fig. 7(a). The OPG was capable of generating pulses with a pulse width of approximately 70 ps and a repetition rate of 1 kHz. The wavelength of output pulse can be adjusted from 1.5 μm to 16 μm. The InF_3 fiber had losses less than 0.5 dB/m in the wavelength range of 1.7 to 4.8 μm and a minimum value of 0.115 dB/m at 3.7 μm. At wavelengths above 4.8 μm, the material losses increased significantly, the losses exceeded 2.6 dB/m at 5.5 μm. Figure 7(b) shows the evolution of the spectrum with pump pulse energy when the InF_3 fiber was pumped at 2020 nm. When the pulse energy reached 8.3 μJ, the generating spectral wavelength covered the entire 2–5 μm band, and its spectral flatness remained <5 dB within the entire band. This was the first time in InF_3 fiber to achieve spectral coverage of 2–5 μm and exhibited good spectral flatness[15]. In 2018, F. Théberge et al used a 1550 nm semiconductor laser as a seed source, and then they pumped the nonlinear fiber after multi-stage amplification. Comparing the SC generated by ZBLAN, InF_3 (sample A), and InF_3 (sample B), it was found that pumping the 20-meter-long InF_3 (sample A) achieved the widest spectral range, covering 1–5 μm, in the 1.91–4.77 μm band, and the spectral flatness was 6 dB[1]. In the same year, J. Gauthier et al achieved supercontinuum broadening in erbium-doped fluoride fiber amplifiers. When the seed source had a repetition rate of 20 kHz and the nonlinear fiber length was 5.8 m, the longest edge of the spectrum was broadened to 4.2 μm. In the range of 3.1–3.85 μm band, the spectral flatness was as low as 1 dB[11].

In addition to the above mentioned cases, soft glass PCFs are equipped with excellent properties of soft glass fibers and PCF. With higher nonlinear refractive index and lower phonon energy, the transmission window can cover near-infrared to mid-infrared[34], which is beneficial to extend the spectral bandwidth. In 2012, M. S. Liao et al used pulsed laser to pump 75-cm-long highly nonlinear tapered tellurite micro-structured fiber with a pulse width of 15 ps, a repetition rate of 80 MHz, and a peak power of 375 W, the 10-dB spectrum spanned 780 nm to 1890 nm[35]. In 2014, M. Klimczak et al implemented SC in an ANDi all solid soft glass PCF. The soft glass PCF was made of in-house synthesized boron-silicate glass and a commercial N-F_2 silicate glass. The dispersion of fiber was flatly distributed in the wavelength range of 1100–2700 nm, and the long wavelength limit of the spectrum was extended to 2300 nm. In the range of 930–2170 nm, the spectral flatness was 7 dB[36]. In 2015, X. Jiang et al used a working wavelength at 1042 nm, ytterbium-doped potas-

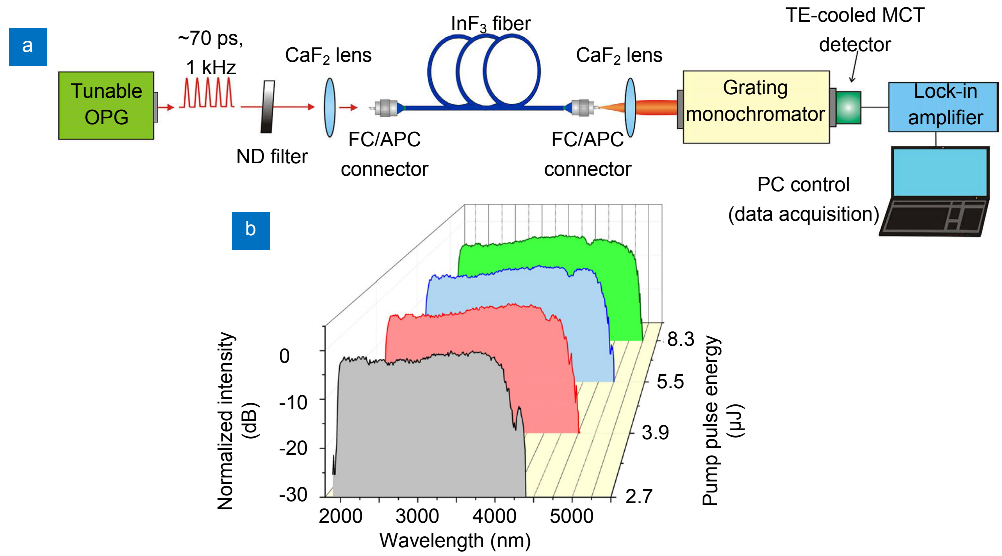

Fig.7 | Experimental setup and spectra for SC generation in the InF_3 fiber. (**a**) Experimental setup. (**b**) Evolution of SC spectrum with pump pulse energy. Figure reproduced from ref.[15].

sium yttrium tungstate laser as a pump source and used 140 fs pulse to pump a 4-cm-long solid-core ZBLAN PCF. The fiber core was slightly elliptical, with a diameter of about 3 μm, a cladding hole spacing of 4.3 μm. The middle cladding channel distributed a triangular gap junction having a diameter of about 1 μm, and a cladding air filling rate was about 88%. Using the maximum pulse energy of 1 nJ to pump the gap junction B, the flatness was better than 10 dB in the range of ~400 nm to 2500 nm, and the spectral flatness fluctuation was less than 3 dB in the range of 800 nm to 2400 nm[37]. In 2017, M. Diouf et al numerically analyzed the generation of 2900–4575 nm ultra-flat coherent SC in the highly nonlinear all-normal dispersion chalcogenide $As_{38.8}Se_{61.2}$ PCF, the spectral flatness was 3 dB[38].

Supercontinuum generation in germania-doped fibers

In recent years, SC sources based on special optical fibers have been extensively researched. The near-infrared supercontinuum of silica-based PCF has achieved commercial success[39]. The usage of soft glass fibers make the SC spectrum further extend to the mid-infrared region. With the advancement of fiber manufacturing processes, making the emergence of highly germania-doped or even pure germania-core fibers have become possible, germania-doped fibers have higher nonlinearity and Raman response than pure silica fibers[40], and better mid-infrared transparency. Compared with soft glass fibers, germania-doped fibers have better compatibility property with silica fibers. Standard splicing technology can weld germania-doped fibers to silica fibers and physical properties are more stable. These excellent properties make germania-doped fiber be a candidate to mid-infrared SC[41,42].

In 2012, V. A Kamynin et al demonstrated that a supercontinuum generation with the wavelength range covered 1.6 μm to 2.7 μm was achieved in a high germania-doped fiber. The nonlinear fiber used in the experiment was a silica-based fiber with 64% germania oxide doped in the core. The pump source used was a Q-switched erbium-doped laser operating at 1.59 μm. The resulting spectrum had a flatness jitter much less than 10 dB in the range of 1.6 μm to 2.7 μm[43]. In 2015, C. C. Wang et al proposed a high GeO_2 concentration cores silica fiber with a step index profile. By adjusting the refractive index and core diameter to change the waveguide dispersion of the fiber, the fiber had a flat normal dispersion in the wavelength range of 1540–2600 nm. In the numerical simulation, the 1550 nm pulse pumped germania-doped fiber, a flat-top supercontinuum wavelength covering 1000–2600 nm was generated[44]. In 2016, L. Yang et al studied the broadening characteristics of the mid-infrared region spectrum when nanosecond pulsed pumping different lengths of germania-core fiber. When the length of the germania-core fiber was 0.8 m, an ultra-wideband SC source with a spectral range of 0.6–3.2 μm was achieved. In the situation of not including pump residuals, the 10-dB spectral bandwidth of the obtained SC is as high as 2281 nm. For the first time, an ultra-wideband supercontinuum source based on a germania-core fiber from the visible region to the mid-infrared region was implemented[45]. In the same year, L. Zhu et al utilized 2 μm thulium-doped Q-switched laser to pump high germania-doped fiber which had 75% germania oxide doped in the core. When the length of germania-doped fiber was 2.8 m, the obtained SC performance was optimal, and the obtained spectral bandwidth spanned 1.9–2.9 μm , the 10 dB bandwidth reached 950 nm[46]. In 2018, K. Yin et al used an all-fiber ultra-fast mode-locked thulium-doped fiber laser as the seed oscillator. The ultra-fast pulse of 1960 nm generated by the oscillator was used to pump the pure germania-core fiber with a core diameter of 8 μm and a cladding diameter of 125 μm. This scheme generated an SC source with a

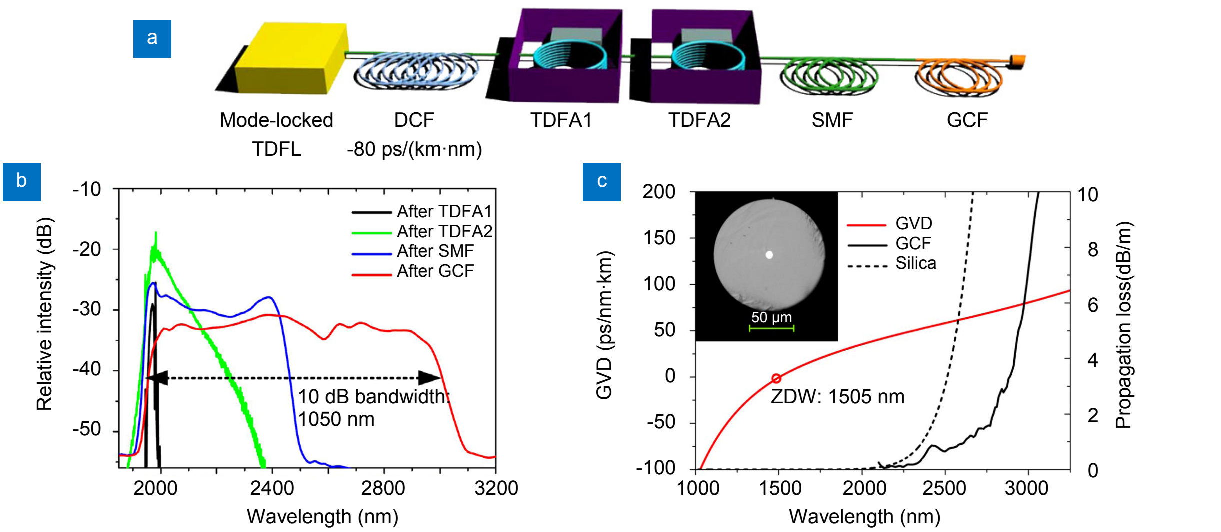

Fig. 8 | (**a**) Experimental setup of supercontinuum generation in germania-core fiber. (**b**) Spectral comparison at different positions. (**c**) Dispersion and loss distribution curve. Figure reproduced from ref.[41].

Table 1 | Summary of typical SC works with specialty optical fibers.

Year	Nonlinear fiber	Spectrum (μm)	Flatness	Output power
2008[17]	PCF	1.06–1.67	8 dB @1.06–1.67 μm	29 W
2010[18]	PCF+HNLF	1.055–1.475	0.7 dB@1.175–1.391 μm	8 W
2010[31]	ZBLAN	0.35–6.28	10 dB @0.565–5.246 μm	-
2015[37]	ZBLAN PCF	0.4–2.5	<3 dB @0.8–2. 4 μm	-
2016[15]	InF_3	2–5	<5 dB @2–5 μm	-
2017[3]	ZBLAN	1.9–4.2	10 dB @1.96–4.05 μm	15.2 W
2018[4]	holmium-doped ZBLAN	2.8–3.9	3 dB @2.93–3.70 μm	411 mW
2018[41]	Germania-core fiber	1.95–3.0	10 dB @1.95–3.0 μm	30.1 W

maximum power of 30.1 W, which was the highest output value of the SC light source reported so far based on the germania-core fiber. The high spectrum flatness of 10 dB was achieved in the range of 1.95–3.0 μm. The experimental setup and the spectra are shown in Figs. 8(a) and 8(b), respectively. Figure 8(c) shows the dispersion and loss distribution of the germania-core fiber used. The zero-dispersion wavelength were at 1505 nm. The 2–3 μm band was in the anomalous dispersion region of the fiber. The transmission loss between 2 μm and 2.8 μm was less than 2 dB/m, much lower than that of silicon fiber. To further broaden the bandwidth, 30.1-W high-power SC source might be used as the pump source of soft glass fibers[41].

Through the introduction of SC generation in the previous several types of optical fibers, it can be found that SC has developed rapidly in recent years, and SC with different spectral widths, different flatness, and different output powers are emerging in an endless stream. Several sets of typical data are listed in Table 1 for comparison.

Conclusions

Supercontinuum sources have developed rapidly in recent years. The emergence of specialty optical fibers has accelerated the development of high-performance supercontinuum sources, making the emergence of broadband flat SC possible. Spectral width and flatness are important parameters to judge the performance of SC sources. In practical applications, the broadband flat SC sources not only can meet the requirements of the system for spectral width, but also can improve the accuracy of measurement. The existing reports can explain the physical mechanism and influencing factors affecting the supercontinuum spectral structure to a certain extent, but there are still no reports about the quantitative analysis of the spectral performance parameters. Moreover, different needs in various fields motive the research of SC generation. Depending on the needs, the quantitative analysis could guide the design of SC generation in terms of seeded pulses as well as nonlinear fibers. So, it is expected to put more effort on the quantitatively analyzing the effects of peak power, initial pulse width, and dispersion parameters of the fiber on the bandwidth and flatness of the supercontinuum, and seeking for more potential applications.

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Competing interests
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