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Invited Papers

Generation and application of high-quality supercontinuum sources

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ABSTRACT

Ultrawideband supercontinua have been generated using ultrashort pulses and zero-dispersion highly nonlinear fiber. However, they have inherent large noise and spectral fine structure. We generated a widely and flatly broadened, low-noise, highly coherent, high-quality supercontinuum and used it to demonstrate ultrahigh-resolution optical coherence tomography in several wavelength regions.

1. Introduction

Advances made in ultrashort-pulse lasers in the last decade have enabled the rapid development of ultrafast nonlinear fiber optics [1]. By exploiting photonic crystal fibers and highly nonlinear fibers, it has become possible to generate widely broadened supercontinua (SC) using nanojoule-order pulses [2–6]. SC are novel, high-power, wideband laser sources which are useful for applications that need wideband light sources.

Generally, an SC has inherent large noise, which causes problems in practical applications. The process of generating an SC has been investigated by several groups, including ours, and the physical mechanism of the large noise has been gradually clarified [7,8] Based on those findings, we have succeeded in generating a low-noise, coherent, smooth, high-quality SC [9–11] that can serve as a wideband coherent laser source.

SC have been used in several applications, such as optical frequency combs [12,13], nonlinear microscopy [14], wideband spectroscopy [15], and ultrahigh-resolution (UHR) optical coherence tomography (OCT) [16,17]. In particular, we have been investigating UHR-OCT using high-quality SC [18–21].

This paper gives a review of our work on high-quality SC generation and its application to UHR-OCT. Recent UHR-OCT results are also described.

2. Ultrawideband supercontinuum generation

It is possible to generate widely broadened SC through the strong nonlinear effects brought about by ultrashort pulses propagating in highly nonlinear fibers [2,3]. In 2001, we succeeded in generating a widely broadened SC using an ultrashort-pulse Er-doped fiber laser and polarization-maintaining highly nonlinear dispersion-shifted fibers (PM-HN-DSFs) [4]. Fig. 1 shows the observed spectra of the SC generated in the PM-HN-DSFs. The temporal width of the pump pulse was 110 fs, and the pulse energy was 0.5 nJ. In the PM-HN-DSFs, the mode-field diameter was 3.7 μm, the dispersion parameter D was 1.0 ps/km/nm, and the dispersion slope was 0.03 ps/km/nm^2 at a wavelength of 1550 nm. The nonlinear coefficient γ was as high as 21 W^{-1} km^{-1}. In this setup, the output pulse from the fiber laser was directly coupled into the PM-HN-DSF.

When the fiber length was 1 m, a few large peaks were generated at both sides of the pump pulse spectrum via self-phase modulation. Then, the bandwidth was broadened further by stimulated Raman scattering, and the spectral shape was gradually flattened due to four-wave mixing, etc. When the fiber length was 5 m, an almost flat, wideband SC extending from 1250 to 1950 nm was generated. This was the first reported generation of an ultrawideband SC around the 1550 nm region.

Using a photonic crystal fiber and SHG pulses from an Er-doped fiber laser system, we also generated a visible to near-infrared (450–1350 nm), ultrawideband SC [22]. The output pulse from the Er-doped fiber laser oscillator was introduced into a fiber chirped-pulse amplifier system, generating a high-power ultrashort pulse. The generated pulse was coupled into a periodically poled $LiNbO_3$ (PPLN) crystal to generate SHG pulses. The temporal width was 107 fs, and the average power was 110 mW at a repetition frequency of 48 MHz. The pulses were then coupled into highly nonlinear photonic crystal fiber (PCF). The diameter of the core was 2.0 μm, and the fiber length was 6.0 m. The zero-dispersion wavelengths of the PCF were 810 and 1910 nm. As shown in

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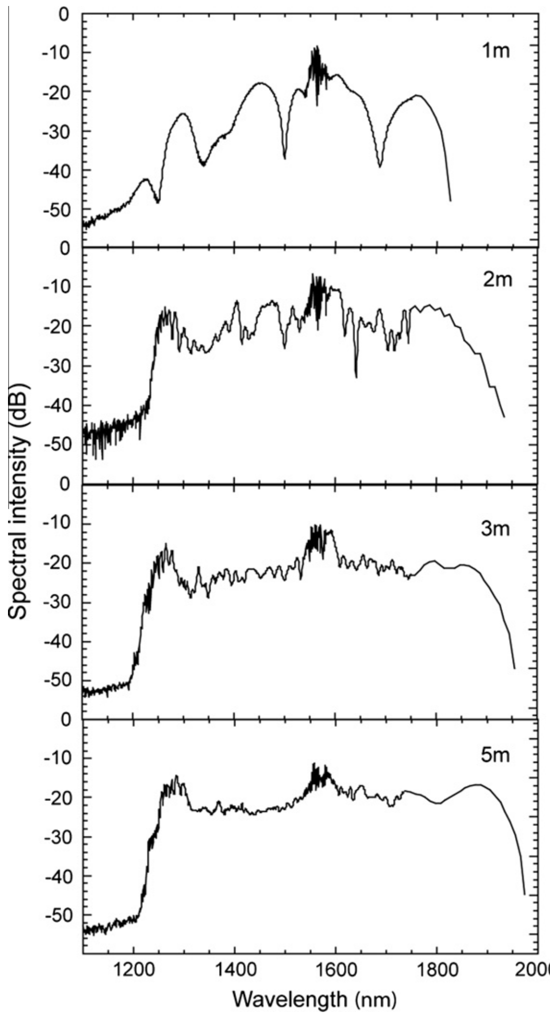

Fig. 1. Spectra of supercontinua generated in highly nonlinear dispersion-shifted fibers of different lengths.

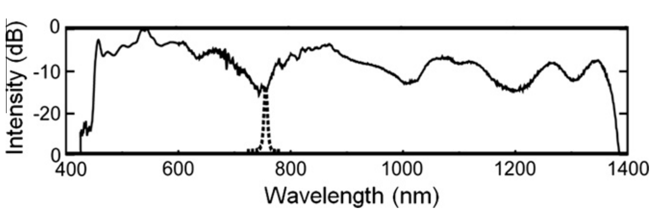

Fig. 2. Spectrum of visible to near-infrared widely broadened SC generated in photonic crystal fiber.

Fig. 2, an ultrawideband SC extending from 450 to 1380 nm was generated.

Although these ultrawideband SC generated in highly nonlinear fiber pumped around the zero-dispersion wavelength appear to be satisfactory, they have inherent large noise and fine spectral structure. Figs. 3 and 4 show the experimental and numerical simulation results for the spectrogram of the SC generated in the PM-HN-DSF. A sonogram system that we developed was used for the measurements in Fig. 3 [23]. A rigorous nonlinear Schrodinger equation was used for the numerical results in Fig. 4 [8]. The spectrum was broadened parabolically owing to third-order dispersion. A soliton pulse was generated at the longer wavelength side, and the shorter wavelength component was trapped by this soliton pulse through cross phase modulation. The spectral fine structure

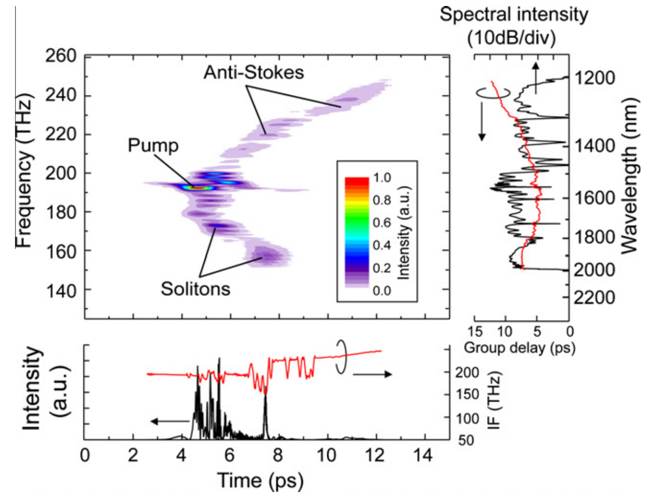

Fig. 3. Observed spectrogram of SC generated in highly nonlinear fiber. A developed sonogram system was used for these measurements [23].

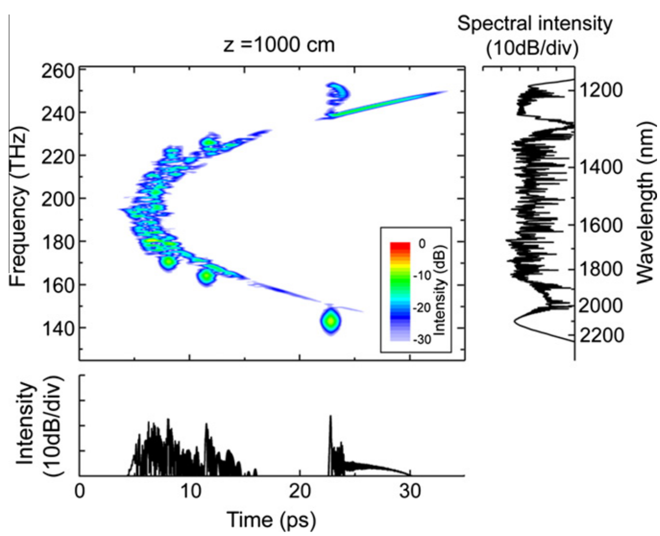

Fig. 4. Numerical simulation results of spectrogram of SC generated in highly nonlinear fiber.

was confirmed experimentally by cross-correlation frequency resolved optical gating (X-FROG) measurements carried out by Gu et al. [24]. These characteristics seriously degraded the noise and coherence properties of the ultrawideband SC. Similar large noise and incoherent properties were also confirmed in an SC generated by cw or nanosecond to picosecond pulses [6].

3. High-quality supercontinuum generation

Considering the previously mentioned results, we tackled the issue of large noise and spectral degradation in the SC generation process, and we succeeded in generating high-quality SC [9–11]. Fig. 5 shows the experimental setup of the system used to generate high-quality SC. The key factors are (1) the quality of the pump pulse and (2) the properties of the nonlinear fiber used for SC generation. For the pump pulse, the low-power pedestal component does not contribute to SC generation, but forms peaks in the spectrum. Therefore, an ideal, pedestal-free pulse is required to generate a flat, smooth SC. In order to prepare a high-quality pulse, a high-power $sech^2$-shaped, transform-limited, ultrashort soliton