Generation of an octave-spanning supercontinuum in highly nonlinear fibers pumped by noise-like pulses

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ABSTRACT

A supercontinuum generation system is developed, which consists of an erbium-doped fiber ring laser, an erbium-doped fiber amplifier, and a 100-m highly nonlinear fiber. Through nonlinear polarization rotation, the fiber ring laser generates a train of noise-like pulses in the form of repetitive picosecond pulse packets consisting of femtosecond noise-like fine temporal structures. The noise-like pulses are amplified before being sent into the highly nonlinear fiber. As a result, an octave-spanning supercontinuum from 1177 nm to 2449 nm is obtained, which has a 20-dB spectral width of 980 nm. Because of the nonlinearity of the fiber amplifier, the duration of the noise-like pulses is shortened while their average power is enhanced. However, the enhanced pulse energy makes the key contribution to the spectral broadening of the resulting spuercontinuum in this study since the highly nonlinear fiber is so long that the effect of the pulse compression on supercontinuum generation is weak.

Keywords: pulse lasers, fiber lasers, mode-locked lasers, ultrafast lasers, supercontinuum generation, nonlinear optics, pulse amplifier, fiber amplifier, noise-like pulses, femtosecond phenomena.

1. INTRODUCTION

Supercontinuum sources, owing to their numerous applications in such areas as microscopy [1], spectroscopy [2], and optical communication [3], have been the object of extensive investigation over the past few decades [4]. Unlike traditional broadband light sources, such as mercury lamps, supercontinnuum possesses the characteristics of single mode, broad and flat spectrum, and high temporal coherence. However, for certain applications, such as optical coherence tomography, optical sensing [5, 6], and optical communications [7], broadband light sources with low temporal coherence are preferred. Therefore, some recent studies have been devoted to the investigation of supercontinuum generation using noise-like pulses [8-13]. The noise-like pulses were composed of sub-nanosecond wavepackets with a fine inner structure of subpicosecond pulses that have stochastically changing durations and peak intensities [14]. Such a unique characteristic of the noise-like pulses leads to a broad spectrum of low temporal coherence, which can therefore be used as pump pulses for the generation of supercontimuum of low temporal coherence.

Different approaches have been proposed for supercontinuum generation using noise-like pulses. For example, in one approach a highly nonlinear fiber was inserted inside a laser ring cavity operating at high pump power levels [15]. As a result, the Raman scatting was considerably excited and a spectrum of 135-nm width is obtained [16]. In another approach a highly nonlinear fiber was placed outside the laser cavity instead and pumped by the noise-like pulses from the laser. A spectral width spanning over several hundreds of nanometers was achieved [8,9]. To increase the spectral width of supercontinuum, yet another approach was to strongly amplify the noise-like pulses before they were launched into a highly nonlinear fiber [10]. As a result, a supercontinuum spectrum spanning from 1208 to 2111 nm was obtained using a 1-m nonlinear fiber pumped by amplified noise-like pulses. In this study, we demonstrate the generation of an octave-spanning supercontinuum from 1177 nm to 2449 nm using a 100-m highly nonlinear fiber pumped by amplified noise-like pulses.

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2. EXPERIMENTAL RESULTS AND DISCUSSION

2.1 Noise-like pulse generation

Figure 1 shows the experimental arrangement for the all-fiber supercontinuum generation system used in this study. The ring cavity consisted of a 0.6-m erbium-doped fiber with a peak absorption coefficient of 80 dB/m at 1530 nm. The erbium-doped fiber was pumped by a pump laser diode delivering a power of 480 mW at 976 nm. The cavity also included a 3-m dispersion compensation fiber with a group velocity dispersion coefficient of –97.7 ps/km-nm at 1550 nm, a polarization dependent isolator to ensure the unidirectional propagation of optical signals but also to limit their polarization direction, a 10/90 coupler to deliver the pulse train out of the cavity, and two polarization controllers to adjust the polarization inside the cavity. The total length of the ring cavity was 12.7 m. By appropriately selecting the orientations of the two polarization controllers, the laser oscillator was able to steadily generate noise-like pulses in the form of repetitive picosecond pulse packets consisting of femtosecond noise-like fine temporal structures. The fundamental repetition rate of the picosecond pulse packets was 15.5 MHz, which indicates that the oscillator generated with one pulse packet per round trip. The average output power from the 10% output port of the coupler was 14 mW, and the pulse energy was 0.9 nJ. The optical spectrum had a peak wavelength at around 1560.9 nm and a 3-dB spectral width of 13.1 nm. The autocorrelation traces of the laser output are shown in Figures 2(a) and (b), from which the pedestal duration and the spike duration were found to be 44.4 ps and 352 fs, respectively. The ratio between the spike peak and the shoulder level of the autocorrelation trace in Figure 2(a) is around 2, which suggests a characteristic of noise-like pulses.

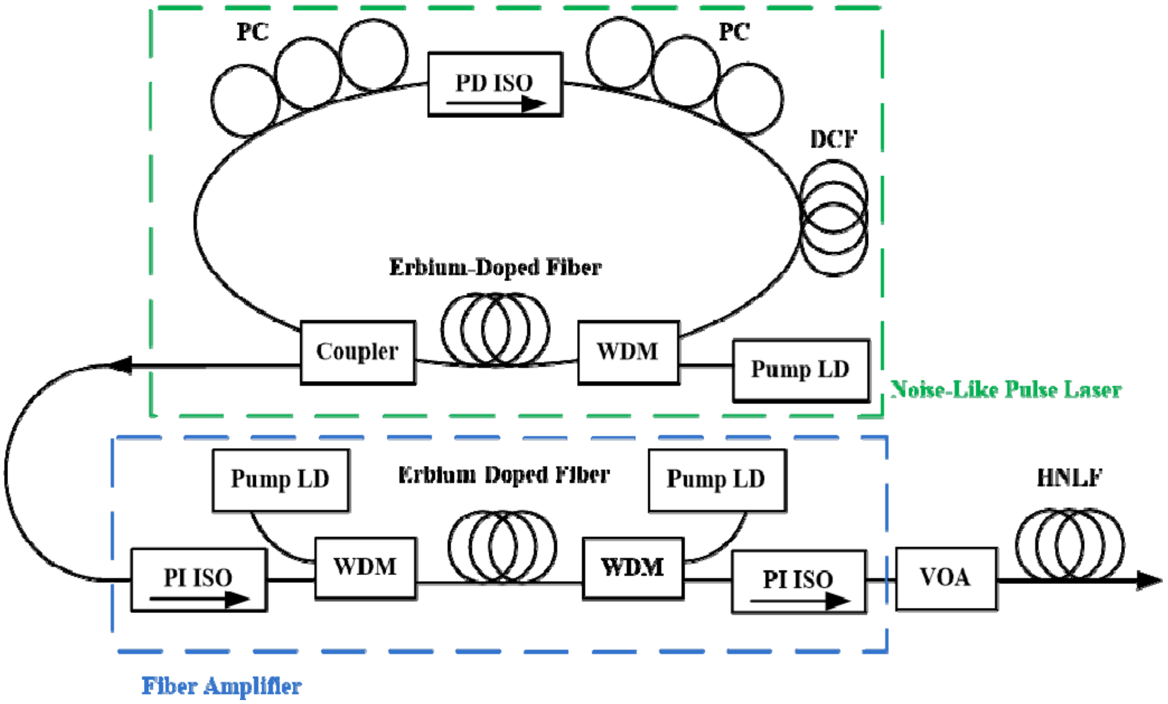

Figure 1. Experimental setup of supercontinuum generation. DCF, dispersion compensation fiber; PC, polarization controller; PD ISO, polarization-dependent isolator; PI ISO, polarization-independent isolator; Pump LD, pump laser diode; HNLF, highly nonlinear fiber; VOA, variable optical attenuator; WDM, wavelength division multiplexer.

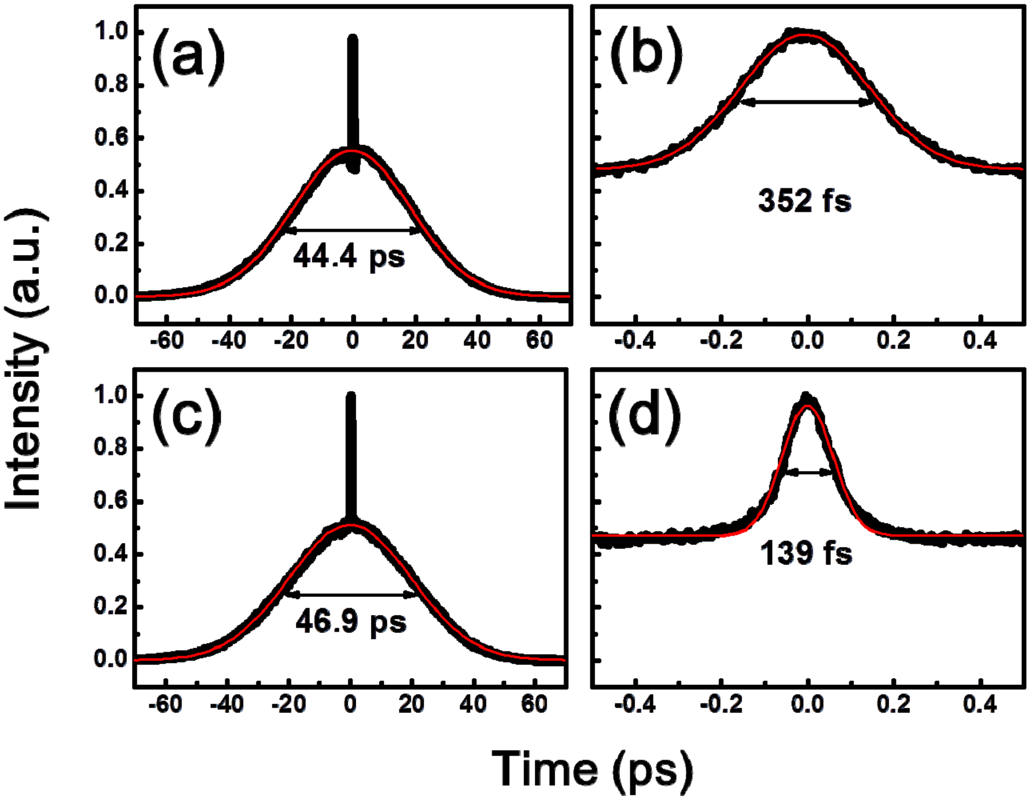

Figure 2. Autocorrelation trace of noise-like pulses before amplification (a) and after amplification (c). (b) and (d) are magnification of the spikes in (a) and (c), respectively. Red curves are Gaussian fitting curves.

2.2 Amplification of noise-like pulses

To increase the average power of the noise-like pulses, the laser output was sent through an erbium-doped fiber amplifier with a bi-directional pump configuration. The amplifier was composed of two 980/1550-nm wavelength-division-multiplexed couplers and two 976-nm pump laser diodes. To ensure unidirectional propagation of the noise-like pulses and to avoid back reflection, two polarization-independent isolators are placed at the input and output ports of the amplifier, respectively. The output power increased with the pump power, as shown in Figure 3(a), where a linear relationship with a slope of 0.19 is observed. The output average power is given as:

$$P_{\mathrm{s}}^{\mathrm{out}} = 0.19 \times P_{\mathrm{p}}^{\mathrm{in}} - 3.39, \tag{1}$$

where $P_{\mathrm{s}}^{\mathrm{out}}$ and $P_{\mathrm{p}}^{\mathrm{in}}$ are the output power and the pump power, respectively. The maximum output power is 202 mW at a pump power level of 1088 mW. While the average power of the noise-like pulses increased, their temporal profile also evolved with the pump power. As seen in Figure 3(b), the peak duration was significantly compressed from 378 fs to 139 fs with the increase of the pump power; by contrast, the pedestal duration increased slightly from 42.7 ps to 46.9 ps. For the range of the pump power under study, the peak duration and the pedestal duration could be compressed by a factor of about 0.4 and 1, respectively. As a result, the peak power of the noise-like pulses was increased not only because of the average power enhancement but also owing to the temporal compression of the pulses.

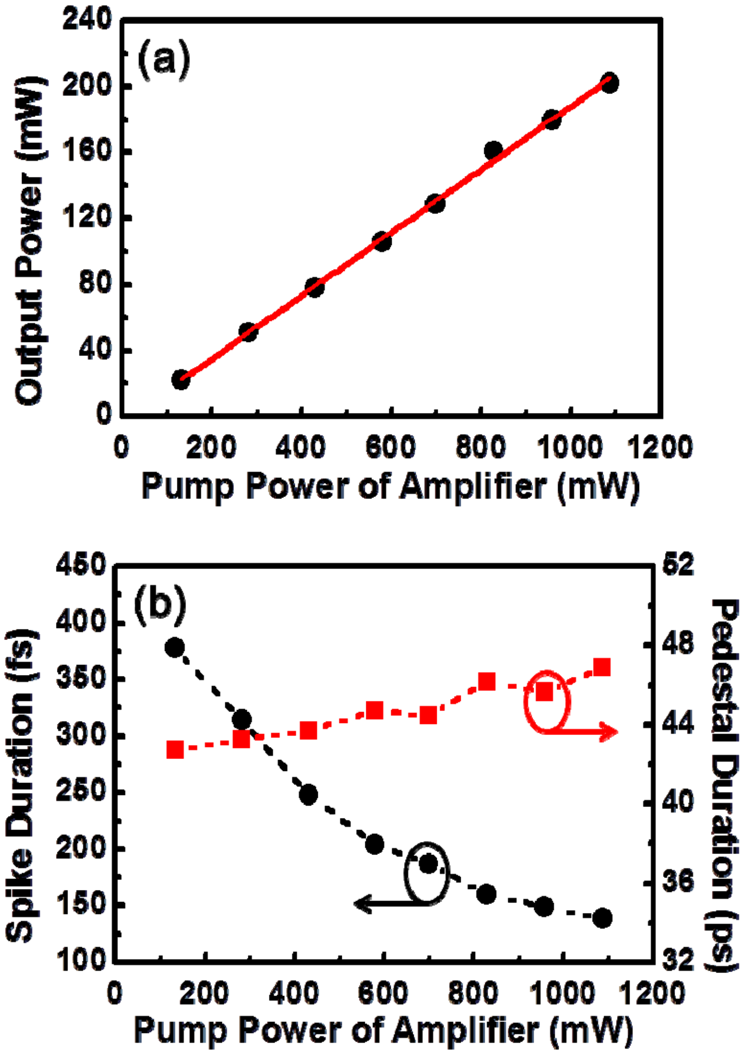

Figure 3. (a) Output power versus pump power of erbium-doped fiber amplifier. The red line represents a linear fit. (b) The spike duration and pedestal duration versus pump power of the amplifier.

2.3 Supercontinuum generation

The amplified noise-like pulses were launched into a 100-m-long highly nonlinear fiber. The effective area and the nonlinear coefficient of the highly nonlinear fiber were 12.5 μm at 1550 nm and 10.7 W^{-1}-km^{-1}, respectively. Two different operating conditions were considered in this study for supercontinuum generation. First, while the pump power of the amplifier was fixed at the maximum level of 1088 mW, the launched average power of the amplified noise-like pulses was adjusted through the variable optical attenuator shown in Figure 1. Under this condition, the spike duration in the autocorrelation trace of the amplified noise-like pulses was maintained at 139 fs throughout the launched power adjustment. Second, while the power attenuation through the variable optical attenuator is kept at the minimum level, the pump power of the amplifier was adjusted to vary the launched power of the amplified noise-like pulses. Under this condition, the spike duration decreased with the launched power. Therefore, the duration of the noise-like pulses obtained under the first operating condition was shorter than that obtained under the second operating condition.

Figure 4(a) shows the spectra of the supercontinua at four different launched powers of the amplified noise-like pulses under the two operating conditions mentioned above. First, the spectra broaden significantly with the average power of the noise-like pulses launched into the highly nonlinear fiber. This is more easily observed in Figure 4(b), where a 20-dB spectral width of each spectrum is defined and demonstrated. At the maximum launched power of 202 mW, which corresponds to a pulse packet energy of 13 nJ, an octave-spanning supercontinuum from 1177 nm to 2449 nm was obtained, which has a 20-dB spectral width of 980 nm. Second, the spectra of the supercontinua depend negligibly on the pulse duration. As demonstrated in our previous study [10], where a highly nonlinear fiber of only 1-m long was used, a shorter duration of noise-like pulses generally generates a broader spectrum of supercontinuum under the same average launched power. Therefore, the result shown in Figure 4 indicates that the length of the highly nonlinear fiber used in this study is so long that even a noise-like pulse of a longer duration but of the same average launched power can excite a similar level of nonlinear effects to achieve a similar supercontinuum spectrum.

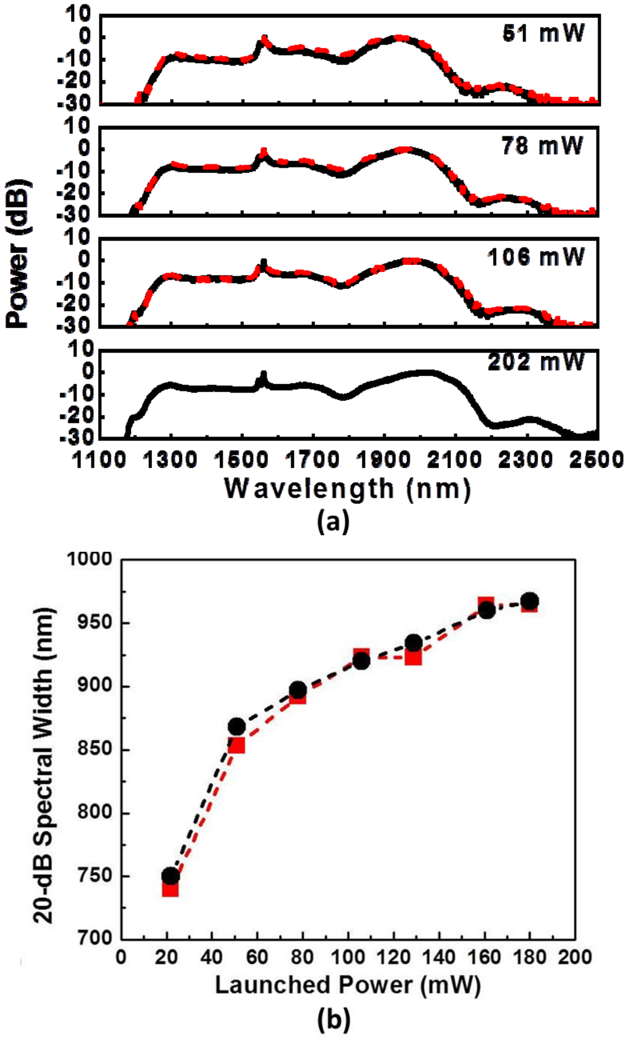

Figure 4. (a) Optical spectra and (b) 20-dB spectral widths of supercontinua at different average powers of noise-like pulses launched into the highly nonlinear fiber. Each launched power studied in (a) is indicated in each plot. Black curves and symbols were obtained when the launched power was adjusted through the variable optical attenuator, while red curves and symbols were obtained when the launched power was changed by varying the pump power of the fiber amplifier.

3. CONCLUSION

By seeding amplified noise-like pulses of 13 nJ pulse energy into a 100-m highly nonlinear fiber, an octave-spanning supercontinuum from 1177 nm to 2449 nm for a 20-dB spectral width of 980 nm was obtained. Because of the nonlinearity of the fiber amplifier, the duration of the noise-like pulses was shortened while their average power was enhanced. In this study, the enhanced pulse energy made the key contribution to the spectral broadening of the resulting spuercontinuum since the highly nonlinear fiber was so long that the effect of the pulse compression on supercontinuum generation was weak.

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