Supercontinuum generation in highly nonlinear fibers using amplified noise-like optical pulses

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Abstract: Supercontinuum generation in a highly nonlinear fiber pumped by noise-like pulses from an erbium-doped fiber ring laser is investigated. To generate ultrabroad spectra, a fiber amplifier is used to boost the power launched into the highly nonlinear fiber. After amplification, not only the average power of the noise-like pulses is enhanced but the spectrum of the pulses is also broadened due to nonlinear effects in the fiber amplifier. This leads to a reduction of the peak duration in their autocorrelation trace, suggesting a similar extent of pulse compression; by contrast, the pedestal duration increases only slightly, suggesting that the noise-like characteristic is maintained. By controlling the pump power of the fiber amplifier, the compression ratio of the noise-like pulse duration can be adjusted. Due to the pulse compression, supercontinuum generation with a broader spectrum is therefore feasible at a given average power level of the noise-like pulses launched into the highly nonlinear fiber. As a result, supercontinuum generation with an optical spectrum spanning from 1208 to 2111 nm is achieved using a 1-m nonlinear fiber pumped by amplified noise-like pulses of 15.5 MHz repetition rate at an average power of 202 mW.

OCIS codes: (320.2250) Femtosecond phenomena; (320.6629) Supercontinuum generation; (320.7090) Ultrafast lasers; (320.7110) Ultrafast nonlinear optics; (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers.

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1. Introduction

Supercontinuum generation in nonlinear fibers using ultrashort pulse pumping has attracted continuous research interest [1] because of its promising and revolutionary applications in numerous areas, such as optical frequency metrology, spectroscopy, optical coherence tomography, and optical communications. Well-defined pump pulses of high pulse energies that have durations ranging from tens to hundreds of femtoseconds are used. Depending on the pump pulse characteristics, such as pulse duration and pulse wavelength relative to the fiber zerodispersion point, the process of supercontinuum generation involves various nonlinear phenomena. They include self-phase modulation, stimulated Raman scattering, four-wave mixing, soliton fission, Raman self-frequency shift, and dispersive wave generation. The resulting supercontinua usually consist of broad spectra over hundreds or even thousands of nanometers with fine structures and with high noise sensitivity [2–5].

Lately, noise-like pulses generated from fiber ring lasers have been proposed for the generation of structureless, broad spectra covering from tens to hundreds of nanometers [6–14]. Such pulses are composed of sub-nanosecond wavepackets with a fine inner structure of sub-picosecond pulses that have stochastically changing durations and peak intensities. This temporal feature leads to a double-scaled autocorrelation trace with a sub-picosecond peak riding upon a wide and smooth sub-nanosecond pedestal, suggesting a characteristic of low temporal coherence. Therefore, noise-like pulses find various applications that take advantage of their low temporal coherence, such as optical metrology, optical sensing [15, 16], optical coherence tomography, and optical communications [17–19]. On the other hand, by taking advantage of their smooth and broad spectra, noise-like pulses have been proposed as pump pulses for supercontinuum generation in nonlinear fibers [20–23].

For supercontinuum generation of an ultrabroad spectrum in a nonlinear fiber, such as one with an octave spanning, pump pulses with high energies are desired, usually a few to tens of nanojoules. However, the typical energy of a pulse from a laser oscillator commonly used as the pump for supercontinuum generation, such as a passively mode-locked fiber laser, is only sub-nanojoules or a few nanojoules. Therefore, amplification of the pump pulses before they are launched into a nonlinear fiber is usually necessary. For well-defined pulses, to minimize unnecessary nonlinear effects while they propagate through an amplifier, it is a common practice to temporally stretch the pulses using extra dispersive media so that the peak power of the pulses is reduced before amplification [3,5,24–26]. Temporal compression of the pulses using additional dispersive media is conducted after amplification to enhance the pulse peak power for broadband supercontinuum generation [3,5,24–26]. For noise-like pulses, it has been experimentally and numerically found that their pulse durations can be hardly broadened or compressed by the dispersive effect [6,9,13]. This observation implies that similar processes of temporal pre-stretching and post-compression using dispersive media are difficult to achieve and thus are not necessary for noise-like pulses. Therefore, in this study, neither temporal pre-stretching nor post-compression using dispersive media is considered; only the effects of amplification on noise-like pulses and their consequences in supercontinuum generation are investigated.

As will be demonstrated in the following analyses, significant nonlinear effects in the amplifier are excited during the amplification process. This results in spectral broadening of the amplified noise-like pulses and significant temporal compression of these pulses. Therefore, simultaneous power amplification and temporal compression of noise-like pulses can be achieved. Increasing the pump power of the amplifier increases the average power of the noise-like pulses. This enhances the nonlinear effects in the amplifier, resulting in a broader spectrum and a shorter duration of the amplified noise-like pulses as the pump power increases. Therefore, by controlling the pump power of the amplifier, the compression ratio of the noise-like pulse duration can be adjusted, providing the flexibility of system operation in a dynamic manner. At a fixed average power of the noise-like pulses launched into a nonlinear fiber, supercontinuum generation with a broader spectrum is feasible due to such temporal pulse compression, which cannot be achieved through the dispersive effect.

2. Experimental setup

A schematic of the supercontinuum generation system used in this study is shown in Fig. 1(a), which consists of a noise-like pulse laser, a fiber amplifier, and a highly nonlinear fiber. The

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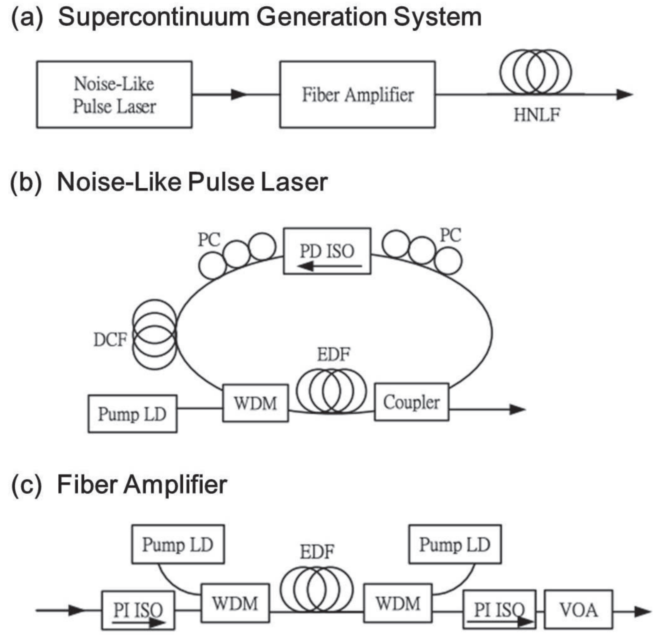

Fig. 1. Schematics of (a) supercontinuum generation system, (b) noise-like pulse laser, and (c) fiber amplifier. HNLF, highly nonlinear fiber; Pump LD, pump laser diode; WDM, wavelength division multiplexer; DCF, dispersion compensation fiber; PC, polarization controller; PD ISO, polarization-dependent isolator; EDF, erbium-doped fiber; PI ISO, polarization-independent isolator; VOA, variable optical attenuator.

noise-like pulse laser is a fiber ring laser, as shown in Fig. 1(b), which has a cavity length of about 12.7 m. The ring cavity includes a 0.6-m erbium-doped fiber (Liekki ER80-8/125) with a peak absorption coefficient of 80 dB/m at 1530 nm and a group velocity dispersion coefficient of 15.7 ps/km-nm [27]. A laser diode (JDSU S30-7602-660) operating at 976 nm with an output power of 480 mW is used to pump the fiber ring laser. A polarization-dependent isolator is used not only to ensure the unidirectional propagation of optical signals but also to limit their polarization direction. Together with the two polarization controllers, a nonlinear switching mechanism can be achieved through nonlinear polarization rotation, which leads to the generation of noise-like pulses. This nonlinear switching is similar to the one commonly used for passive mode-locking in fiber ring lasers. A 3-m dispersion compensation fiber with a group velocity dispersion coefficient of −97.7 ps/km-nm at 1550 nm is used for well-defined pulse generation, which is not our consideration in this study. With or without the dispersion compensation fiber, noise-like pulses can be generated by properly adjusting the polarization controllers [6]. About 10% of the laser power is coupled out of the ring cavity, resulting in an average output power of 14 mW, which is sent into the fiber amplifier.

As shown in Fig. 1(c), a similar erbium-doped fiber (Liekki ER80-8/125) of 1.2 m length is used as the gain medium for the fiber amplifier. Two laser diodes (JDSU S30-7602-660 and S30-7602-600) both operating at 976 nm with a total power reaching up to 1088 mW are used to bi-directionally pump the fiber amplifier. Two polarization-independent isolators are used to prevent reflection back to the noise-like pulse laser and the fiber amplifier. A variable optical attenuator is used to adjust the power of the amplified pulses that are launched into the highly nonlinear fiber. The length, effective area, and nonlinear coefficient of the highly nonlinear fiber

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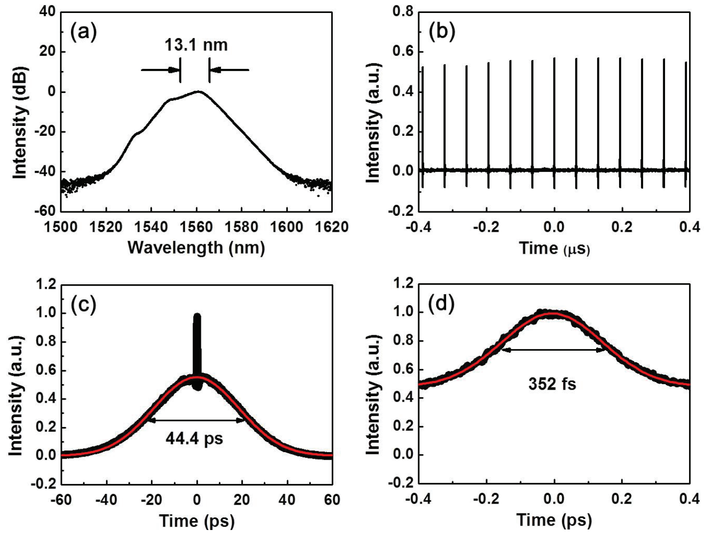

Fig. 2. (a) Optical spectrum, (b) pulse train, (c) autocorrelation trace, and (d) magnification of autocorrelation trace of noise-like pulses. Red curves in (c) and (d) are Gaussian fitting of the pedestal and the peak, respectively.

(OFS HNLF Zero-Slope) are 1 m, 12.5 μm^2 at 1550 nm, and 10.7 W^{-1} km^{-1}, respectively.

An optical spectrum analyzer (Anritsu MS9740A) covering a spectral range from 600 to 1750 nm is used to analyze the spectral features of the noise-like pulses at the outputs of the fiber ring laser and the fiber amplifier. To fully characterize the ultrabroad band of the supercontinuum obtained at the output of the highly nonlinear fiber, another optical spectrum analyzer (APE WaveScan) covering a spectral range from 1000 to 2600 nm is used instead. The pulse train is recorded with a 45-GHz photodiode (Discovery Semiconductors DSC 10H) and displayed on a 3-GHz real-time oscilloscope (Agilent DSO80304B). A background-free intensity autocorrelator (Femtochrone FR-103XL) is used to study the auotocorrelation traces of the noise-like pulses.

3. Results and analyses

3.1. Noise-like pulses before amplification

Figure 2(a) shows the typical optical spectrum of the noise-like pulses at the output of the fiber ring laser. The spectrum has its peak wavelength at around 1560.9 nm and a 3-dB spectral width of 13.1 nm. The corresponding pulse train presented in Fig. 2(b) shows a repetition rate of 15.5 MHz with a randomly varying peak intensity among pulses. To analyze the pulse characteristics, the autocorrelation trace of these optical pulses is investigated, as shown in Figs. 2(c) and 2(d). A 352-fs peak rides upon a wide and smooth 44.4-ps pedestal, and the intensity ratio of the pedestal to the peak is about 0.5. Note that the durations of the peak and the pedestal are defined as the full widths at half maximum of their Gaussian fitting curves, as shown in red in the figures. The occurrence of the wide and smooth sub-nanosecond pedestal indicates that the optical fields under investigation are composed of sub-nanosecond wavepackets with a fine inner structure of pulses that are temporally separated in a random, complex fashion [28]. The sub-picosecond peak, on the other hand, suggests that the pulses within the wavepackets have sub-picosecond temporal durations [28]. The pedestal-to-peak intensity ratio of 0.5 indi-

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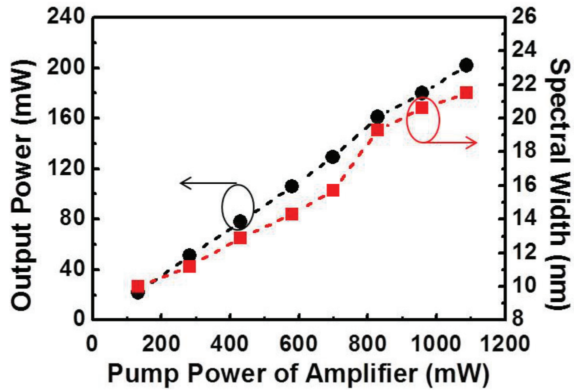

Fig. 3. Output power (black symbols) and 3-dB spectral width (red symbols) of amplified noise-like pulses in terms of pump power of the fiber amplifier.

cates that the spectral components of the optical fields are highly uncorrelated and therefore the optical fields have low temporal coherence [9, 12, 14]. Such a low-coherence characteristic suggests a substantial fluctuation in shot-to-shot optical spectra, each individual of which is highly structured. The ensemble average of the shot-to-shot spectra gives rise to a smooth optical spectrum obtained using a conventional spectrum analyzer [9, 12, 14], as that shown in Fig. 2(a). The pedestal-to-peak intensity ratio of 0.5 also suggests that the intensities of the sub-picosecond pulses vary randomly [6, 9, 12]. This leads to the intensity fluctuation of the wavepackets; such fluctuation is seen in the pulse train presented in Fig. 2(b). The observed characteristics of the autocorrelation trace together with the broad and smooth optical spectrum are identifying features common to all reported noise-like pulses in the literature [6–14].

3.2. Amplification of noise-like pump pulses

By sending the noise-like pulses through the fiber amplifier, their average power increases linearly with the pump power of the amplifier at a slope of 0.19, as shown in Fig. 3. A maximum output power of about 202 mW can be achieved at a pump power level of 1088 mW, leading to an amplification of 11.6 dB. In addition, the optical spectrum of the amplified noise-like pulses broadens significantly, which indicates that the noise-like pulses experience significant nonlinear optical effects during the amplification process. Note that it is a common practice to temporally stretch well-defined pulses using extra dispersive media before amplification in order to lower their peak power and therefore to avoid inducing excessive nonlinear effects in amplifiers. Such temporal stretching is not conducted in this study because it is not effective and not necessary for the noise-like pulses. To demonstrate the spectral broadening, the 3-dB spectral width is also presented in Fig. 3 as a function of the pump power of the amplifier. At pump powers below 500 mW, though the spectral width increases monotonically with the pump power, it is actually smaller than its input value of 13.1 nm, indicating the effect of gain narrowing [24, 25]. By contrast, at pump powers above 500 mW, the spectral width becomes larger than its input value and continues to increase with the pump power. This result suggests that other nonlinear effects, such as self-phase modulation, counteract the gain narrowing effect [24, 25] to broaden the spectrum at high pump powers. The spectrum is broadened up to 21.5 nm at a pump power of 1088 mW, leading to an enhancement of 1.64 folds.

The effect of this spectral width enhancement on the temporal feature of the amplified noise-like pulses is presented in Figs. 4(a) and 4(b) at the pump power of 1088 mW. A similar double-

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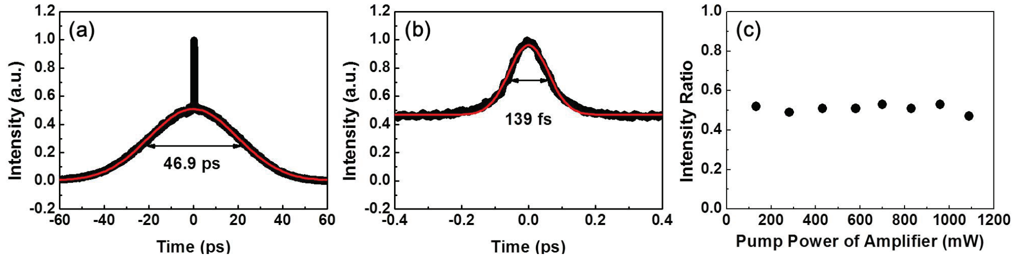

Fig. 4. (a) Autocorrelation trace, (b) magnification of autocorrelation trace, and (c) ratio of the pedestal level to the peak in the autocorrelation trace as a function of amplifier pump power for amplified noise-like pulses. Red curves in (a) and (b) are Gaussian fitting of the pedestal and the peak, respectively.

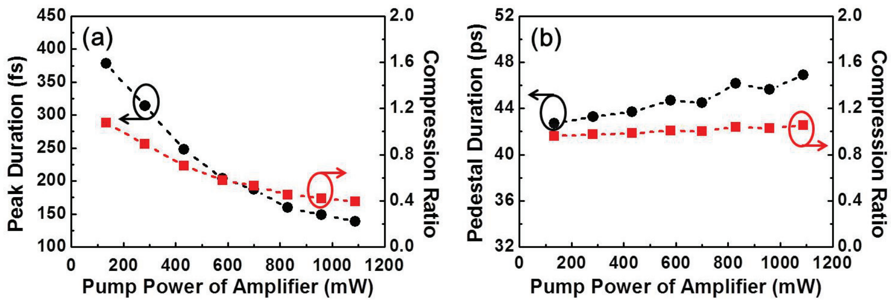

Fig. 5. Duration (black symbols) and compression ratio (red symbols) of (a) the peak and (b) the pedestal in the autocorrelation traces in terms of pump power of the fiber amplifier.

scaled autocorrelation trace is observed with a pedestal-to-peak intensity ratio of 0.5. Similar autocorrelation traces and pedestal-to-peak intensity ratios are observed at other pump powers of the amplifier under study, as presented in Fig. 4(c), suggesting a similar noise-like characteristic after amplification. As shown in Figs. 4(a) and 4(b), the peak duration of the autocorrelation trace reduces significantly down to 139 fs at the pump power of 1088 mW, suggesting that the temporal durations of the amplified noise-like pulses are similarly shortened. Meanwhile, the pedestal duration increases only slightly to 46.9 ps, suggesting that the wavepackets expand in a similar fashion. In fact, as shown in Fig. 5(a), the peak duration compresses monotonically with the pump power of the amplifier, reaching a compression ratio of about 0.4 at the maximum pump power. This feature results from the fact addressed in Fig. 3 that the spectral width increases with the pump power. Note that the peak duration after amplification is, however, longer than that before amplification at pump powers below 200 mW due to the gain narrowing effect that reduces the spectral width. By contrast, as shown in Fig. 5(b), the pedestal duration only varies slightly over the range of amplifier pump power under study, maintaining a compression ratio of about 1.

3.3. Supercontinuum generation using amplified noise-like pump pulses

The ability to shorten the noise-like pulses through the amplification process provides an advantage in generating a broader spectrum of supercontinuum pumped by such pulses at a fixed average power. Figure 6(a) demonstrates the spectra of the supercontinua at four different average powers of the amplified noise-like pulses launched into the highly nonlinear fiber. Two

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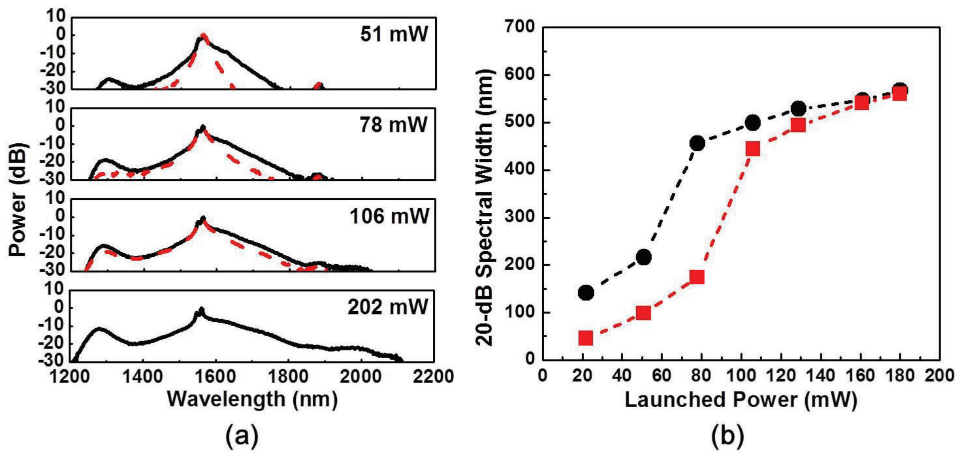

Fig. 6. (a) Optical spectra and (b) 20-dB spectral widths of supercontinua at different powers of noise-like pulses launched into the highly nonlinear fiber. Each launched power studied in (a) is indicated in each plot. Black curves and symbols are obtained when the launched power is adjusted through the variable optical attenuator, while red curves and symbols are obtained when the launched power is changed by varying the pump power of the fiber amplifier.

different operating conditions are considered in each plot. First, while the pump power of the amplifier is fixed at the maximum level of 1088 mW, the launched power of the amplified noise-like pulses is adjusted through the variable optical attenuator shown in Fig. 1(c). Under this condition, the peak duration in the autocorrelation trace of the amplified noise-like pulses is 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 is adjusted to vary the launched power of the amplified noise-like pulses. Under this condition, the average power of the amplified noise-like pulses increases while the peak duration of their autocorrelation trace decreases with the launched power. The launched powers of 51, 78, 106, and 202 mW indicated in Fig. 6(a) correspond to amplifier pump powers of 282, 431, 580, and 1088 mW, respectively. The corresponding peak durations are 314, 248, 204, and 139 fs, respectively. Therefore, for the same launched power, the duration of the noise-like pulses obtained under the first operating condition is generally shorter than that obtained under the second operating condition.

Figure 6(a) clearly demonstrates the advantage of using noise-like pulses of shorter temporal durations for a broader spectrum of supercontinuum generation: at the same average launched power, the supercontinuum spectrum increases with the temporal shortening of the noise-like pulses. As the launched power is increased, the difference in the pulse duration becomes smaller between the two operating conditions; therefore, the two supercontinuum spectra become more similar. At the launched power of 51 mW, where the pulse duration differs by more than 2 folds between the two operating conditions, it is observed that short pulses are in favor of generating long-wavelength components. Similar observations are found at launched powers of 78 and 106 mW even though they are not as evident due to the smaller difference in the pulse duration between the two operating conditions. At the launched power of 202 mW, where the two operating conditions have the same shortest pulse duration of 139 fs in this study, an ultrabroad spectrum of supercontinuum spanning from 1208 to 2111 nm is generated. A wider and flatter spectrum can be obtained if a nonlinear fiber of a larger length is used [20], which is particularly beneficial for the emergence of long-wavelength components mainly due to the nonlinear effect of Raman self-frequency shift [1, 23]. Note that, under the first operating condition where the correlation peak duration of the noise-like pump pulses is fixed, a higher launched power generates a wider and flatter supercontinuum spectrum of substantial long-wavelength components, as shown in Fig. 6(a). This result agrees with the observations reported in the literature using either well-defined or noise-like pump pulses for supercontinumm generation [2, 20, 22, 23]. Since the Raman self-frequency shift contributes to the generation of long-wavelength components in supercontinuum generation [1, 22], it plays a key role in generating wider and flatter spectra of these supercontinua. To quantify the spectral span of each generated supercontinuum for further comparison and analysis, the 20-dB spectral width is experimentally estimated. Figure 6(b) presents the spectral width as a function of the launched power for the two operating conditions. As observed, a broader spectrum is generally obtained under the first operating condition for a given launched power. The difference in spectral width between the two operating conditions decreases with the launched power as the two supercontinuum spectra become more similar to each other.

4. Conclusion

Supercontinuum generation in a highly nonlinear fiber pumped by noise-like pulses from an erbium-doped fiber ring laser is investigated. To generate ultrabroad spectra, a fiber amplifier is used to boost the power launched into the highly nonlinear fiber. Since the temporal durations of the noise-like pulses are hardly broadened or compressed by the dispersive effect, temporal pulse stretching and compression using extra dispersive media before and after amplification, respectively, are both not considered in this investigation. Therefore, this study emphasizes the effects of amplification on the noise-like pulses and their consequences in the supercontinuum generation. After amplification, not only the average power of the noise-like pulses is enhanced, but the spectrum of the pulses is also broadened due to nonlinear optical effects in the fiber amplifier. This leads to a reduction of the peak duration in their autocorrelation trace, suggesting a similar extent of pulse compression; meanwhile, the pedestal duration increases only slightly, suggesting that the noise-like characteristic is maintained. By controlling the pump power of the fiber amplifier, the compression ratio of the noise-like pulse duration can be adjusted. At a given average power of the noise-like pulses launched into the highly nonlinear fiber, generation of a broader supercontinuum spectrum, up to 3 times broader, is therefore feasible by taking advantage of this pulse compression through the amplification process. As a result, a supercontinuum spectrum spanning from 1208 to 2111 nm is achieved using a 1-m nonlinear fiber pumped by amplified noise-like pulses of 15.5 MHz repetition rate at an average power of 202 mW. Besides supercontinuum generation, the features of temporal compression and spectral broadening of these amplified noise-like pulses may find useful applications in, for example, optical metrology, optical sensing, optical coherence tomography, and optical communications.

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