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Low noise supercontinuum generated in the photonic crystal fiber for microwave photonic applications

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Low amplitude noise and timing jitter are important for application of supercontinuum sources in radio-over-fiber systems and photonic signal processing of microwave signals. We experimentally demonstrate that supercontinuum generated in the short highly nonlinear normal dispersion photonic crystal fiber (PCF) exhibits lower amplitude noise and timing jitter than that generated in the anomalous dispersion single mode fiber. The supercontinuum generated in the highly nonlinear photonic crystal fiber at normal dispersion could be a good solution for applications in microwave photonics.

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1. Introduction

The broadband supercontinuum generation currently attracts a lot of attention because of its enormous potential applications, and optical-fiber based supercontinuum sources have been studied intensively in the recent years [1-5]. Now the physics underlying supercontinuum generation is generally well understood. Dispersion plays an important role in the supercontinuum generation in the optical fibers. The development of ultrashort pulse lasers as well as highly nonlinear specialty fibers (such as photonic crystal fibers, tapered fibers and highly nonlinear dispersion-shifted fibers) enables us to easily generate broadband supercontinuum. However, most of the supercontinuum sources demonstrated have the problems such as lack of spectral flatness, large noise, polarization sensitivity and so on. For practical applications, especial in radio-over-fiber systems and photonic signal processing of microwave signals [6-7], low amplitude noise and timing jitter are important to achieve the required system performances. The stability of supercontinuum normally depends on the perturbations of the intensity and the phase of the pump laser [8-9], which causes the degradation of the noise performance.

For supercontinuum generation in the anomalous dispersion regime, the modulation instability (MI) which may perturb the high-order soliton dynamics and has significant contribution to the spectral broadening arises, and the input pump noise can be noticeable amplified along the optical fiber through MI gain [10-12]. The use of dispersion decreasing fibers can improve the amplitude noise performance by avoiding the high-order soliton breakup. The amplitude noise amplification arises from nonlinear amplification of input pump noise and spontaneous Raman scattering [13-15], and strongly depends on the input pulse duration and chirp. The amplitude fluctuation of supercontinuum can be as large as 50% for certain input laser pulse parameters [13-14]. The input pump amplitude noise will also given rise to significant increase on phase noise of generated supercontinuum. Theoretical simulation shows that the phase noise also depends on fiber length, pulse energy, pulse duration and initial chirp [16]. Since MI does not occur in the normal dispersion regime, in principle, supercontinuum generated in the normal dispersion fiber is stable. Theoretical and numerical analysis on noise performances has been carried out [17-18]. Recently, noise performances of supercontinuua generated at different regimes have been experimentally analyzed [19].

Here we experimentally demonstrate that supercontinuum generated in the short highly nonlinear normal dispersion photonic crystal fiber (PCF) exhibits lower amplitude noise and timing jitter than that generated in the anomalous dispersion single mode fiber.

2. Experiment and discussion

2.1 Experimental setup and supercontinumm generation

Fig. 1 shows a schematic diagram of the experimental setup. A modelocked fiber laser operating at 1540 nm is used as a pump source. It produce ~500 fs pulse train with an average power 3 mW at a repetition rate of 20 MHz. The polarization controller is inserted to determine polarization dependency of the supercontinuum. A 1nm tunable bandpass filter is used to slice the supercontinuum for timing jitter and amplitude noise measurement at different wavelengths. The measurement range across the supercontinuum is limited by the tunable range of the filter. The tunable attenuator is accordingly adjusted to provide the same power value for noise measurement. A 10 m highly nonlinear PCF with the dispersion of ~ -1.5 ps/km/nm and a 2 km single mode fiber with the dispersion of ~ 17 ps/km/nm at 1550 are used to generate supercontinua for comparison. The bandwidth of the generated supercontinuum is measured to be >40nm in the PCF and extends >100nm in the single mode fiber, as shown in Fig. 2. When the polarization state of the polarization controller is changed, the sumpercontinuum generated in the PCF remains unchanged, while the supercontinuum in the single mode fiber changes accordingly. The optical spectrum analyzer and the RF spectrum analyzer are used to observe the output spectrum and measure the noise performance at different wavelengths, respectively.

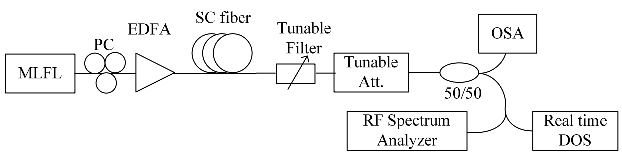

Fig. 1 Experimental setup. MLFL: modelocked fiber laser, PC: polarization controller, EDFA: Erbium-doped fiber amplifier, OSA: Optical spectrum analyzer, DOS: digital oscilloscope.

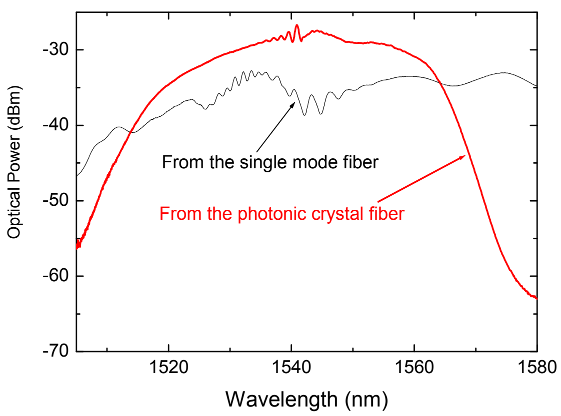

Fig. 2. Supercontinuua generated in the photonic crystal fiber and the single mode fiber.

2.2 Noise analysis and measurement

As mentioned above, the amplitude noise and other parameters of the input pulses influence the amplitude noise of the output supercontinuum, especially in the anomalous dispersion regime. In addition, small amount of the amplitude noise on the input pulse will be converted to phase noise by Kerr effect, which results in an increase of the timing jitter. The phase noise occurs because the Kerr effect makes the index of refraction intensity dependent, $n = n_0 + n_2 I$, where n_0 is the linear index, n_2 is the nonlinear index, and I is the intensity of the light in the fiber core. Carrier-envelope phase noise arises after a pulse propagates a distance l_0 from the light frequency ω accumulation of a differential phase between the pulse carrier and envelope. The nonlinear contribution to the carrier-envelope phase change is directly proportional to the dispersion of n_2 and the change in intensity (ΔI), given by $\Delta\phi_{NL} = \omega l_0 / c (dn_2/d\omega)\, \Delta I$.

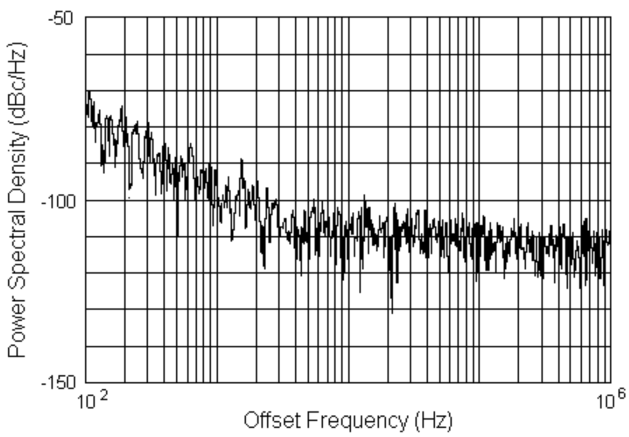

Fig. 3. Single sideband noise spectral density of measured pulse.

We characterize the amplitude noise and timing jitter of the supercontinuum at different wavelengths by measuring the noise sideband of the fundamental mode and the higher-order harmonic using the RF spectrum analyzer. Each side band was acquired over the carrier offset frequency range 100 Hz to 1 MHz. The noise level of the noise sideband is normalized against carrier power and bandwidth resolution and expressed in dBc/Hz, such as in the Fig.3. Above 1 MHz, the noise mainly comes from the detector noise. Amplitude noise and timing jitter have different contributions to the single sideband noise spectrum for different harmonics. The integration of the normalized single sideband noise spectrum over measurement bandwidth related to amplitude noise and timing jitter can be given by [20]

$$\int_{f_{low}}^{f_{high}} L_n(f)df = \frac{\sigma_A^2}{2} + (2n\pi f_M)\frac{C_{AJ}}{2} + (2n\pi f_M)^2 \frac{\sigma_J^2}{2} \quad (1)$$

where $L_n(f)$ is the sideband noise spectral density function, f is the carrier offset frequency, f_M is the repetition rate of the pulse, n is the harmonic order number, σ_A is the amplitude noise, σ_J is the total timing jitter and C_{AJ} is the cross-correlation between pulse timing jitter and amplitude noise. The factor of 2 occurs because we measure single sideband noise.

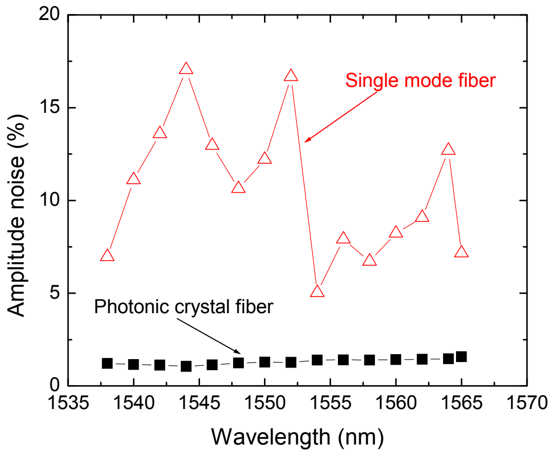

Fig. 4. Amplitude noise comparison measured with the RF spectrum analyzer.

From the above analysis, we can know that the fundamental harmonic mainly shows amplitude noise and the timing jitter appears in higher harmonics, increasing as harmonic number squared. In the experiment, we measure the amplitude noise with the sideband noise spectrum of the fundamental harmonic, and timing jitter with that of 300^{th} harmonic. Fig. 4 depicts the measurement results at different wavelengths for two kinds of fibers. The amplitude noise of the supercontinuum generated in the PCF is measured to be within 1.6 %. The noise profile is nominally flat and increases by ~0.5 % at low power spectral density tails. However, the amplitude noise of the supercontinuum generated in the single mode fiber is above 5% and varies from 5% to 17 %. We first measure the timing jitter σ_{J-P} (155 fs) of the pump laser, and then measure the timing jitter σ_J at different wavelengths of the supercontinuum, as shown in Fig. 5.

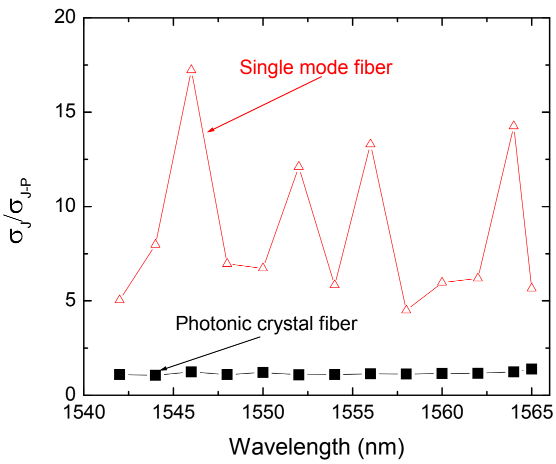

Fig. 5. Timing jitter for supercontinua at different wavelengths for two kinds of fibers.

We show that the timing jitter of the supercontinuum generated in the PCF closely follows the timing jitter of the pump laser and the total degradation is < 2x. The largest timing jitter degradation is measured at the tails of the continuum source with lower power density. The timing jitter of the supercontinuum generated in the single mode fiber increases above 5x due to delicate interplay between the nonlinear phase shift and the group velocity dispersion.

3. Conclusions

The amplitude noise and the timing jitter of the supercontina generated in the highly nonlinear photonic crystal fiber and the single mode fiber are experimentally investigated. We show that the supercontinuum generated in the short highly nonlinear normal dispersion photonic crystal fiber have much lower amplitude noise and timing jitter than that generated in the anomalous dispersion single mode fiber. So the supercontinuum generated in the normal dispersion highly nonlinear photonic crystal fiber could be a good solution for applications in microwave photonics.

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