Multiwatt octave-spanning supercontinuum generation in multicore photonic-crystal fiber

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High-power supercontinuum spanning over more than an octave was generated using a high power femtosecond fiber laser amplifier and a multicore nonlinear photonic crystal fiber (PCF). Long multicore PCFs (as long as 20 m in our experiments) are shown to enable supercontinuum generation in an isolated fundamental supermode, with the manifold of other PCF modes suppressed due to the strong evanescent fields coupling between the cores, providing a robust 5.4 W coherent supercontinuum output with a high spatial and spectral quality within the range of wavelengths from 500 to 1700 nm. © 2012 Optical Society of America

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Supercontinuum (SC) generation is a nonlinear optical phenomena characterized by the dramatic spectral broadening of intense light passing through a nonlinear material [1]. Photonic crystal fibers (PCFs) with appropriate zero dispersion wavelength and small mode area offering high nonlinearity are necessary for efficient SC generation. However, the small fiber core always limits the average power of the SC sources to a few watts. Through a series of PCF postprocessing methods [2–4], Chen et al. [2] expanded the core diameter of the PCF at the input end and obtained 35.6 W high power all fiber SC. Travers et al. [3] used a series of mode matching single mode fibers for low-loss splicing with a small-core PCF and enabled the scaling of the SC average power to 50 W pumped by a continuous-wave laser. Multicore PCFs, because of their large effective mode area and reduced heat- and stress-induced beam distortions, offer attractive solutions for power upscaling of fiber lasers and nonlinear-optical components [5]. Q-switched [6] and mode-locked multicore PCF lasers [7,8] with a pulse energy up to 2.2 mJ [6] and pulse peak power as high as 150 MW [7] have been demonstrated. Multicore PCFs also find growing applications as sensing elements [9] and optical switches [10]. An ultrasensitive refractive index sensor has been realized based on a directional coupler architecture in a dual-core PCF [9]. As a nonlinear medium for SC generation, multicore PCFs have larger mode area while the dispersion curve only changes a little comparing to single-core PCF with the same cladding air-filling fraction. Optical fields propagating in the cores are coupled evanescently, resulting in what are called supermodes. The in-phase supermode, where all cores have the same phase, has the preferable Gaussian-like far-field intensity distribution [11]. These properties inspire us to explore the power enhanced SC generation with multicore PCF.

In this paper, we focus on investigating the supermode and nonlinear properties of a seven-core PCF. The femtosecond pulses laser is utilized as a seeding source for SC generation, which has good coherence and stability. The spectrum is greatly broadened in this fiber and robust passive synchronous phasing in the cores is observed when the fiber length increased to 20 m.

Experiments were performed with the use of a femtosecond Yb-doped large mode area PCF laser amplifier. The amplifier developed in a stretcher-free configuration, delivering laser pulses with a central wavelength of 1038 nm and a maximum average power of 16 W at a pulse repetition rate of 49 MHz. A grating compressor dechirped the output pulses down to 80 fs. An optical isolator is placed at the output of the amplifier to prevent light feedback into the laser system. The polarization of the input pulses is controlled with a half-wave plate placed in front of the microscope objective.

The seven-core silica PCF was designed at the Ultrafast Laser Laboratory and manufactured by Wuhan National Laboratory of Optoelectronic, shown in Fig. 1. The fiber cladding lattice has a pitch of 2.62 μm and an air hole size of 1.43 μm. The air-filling fraction is designed to provide a zero dispersion wavelength approaching the central wavelength of pump laser while retaining sufficient coupling strength between adjacent cores so as to be combined coherently with a unit phase. According to our measurements and finite-element analysis, the zero-dispersion wavelength of the in-phase supermode of the seven-core fiber is around 1025 nm. The fiber ends are simply cleaved without any further postprocessing. The output radiation was coupled into a high-resolution spectrometer (ANDO 6315A) to record spectrum and into beam analyzer for near- and far-field measurements.

To study the excitation of supermodes, a fiber length of 5 cm was chosen. The launched average power is set to 2 W. Laser radiation was simultaneously coupled into the seven cores by focusing a laser beam onto the front end of the fiber to provide a uniform illumination of all the cores. The coupling coefficient in our experiments was
around 60%. The output mode distribution features a superposition of several supermodes and dramatically changes in response to small variations in the polarization of the input pulses, pump beam incoupling geometry, as well as bends and stresses in the fiber. The coexistence of several supermodes was verified by the far-field beam profile. Figures 2(a) and 2(b) show two typical far-field beam profiles produced by red-light, ~650 nm signals generated in the cores through nonlinear-optical spectral transformation of 1038 nm femtosecond laser pulses. It is remarkable that the interference patterns have different symmetry while keeping noticeable visibility. The corresponding output spectrum is shown in Fig. 3(a) stretching from 650 to 1200 nm. The coexistence of several supermodes is manifested in a well-resolved interference fringes. The fringe period slightly increases with wavelength from ~5.6 nm at 760 nm to ~8 nm at 1200 nm. The most striking feature of the interference fringes is that its visibility approaches 1 for most of the SC spectrum.

An increase in the fiber length makes the spectral interference fringes sparser and decreases their visibility. When the fiber length increases to more than 20 m, the modulation of the SC spectrum is completely suppressed [Fig. 3(b), black line]. Strong water absorption at wavelengths around 1400 nm is introduced during the fiber fabrication and can be avoided with careful handling. The output beam profile of a 20 m long PCF features a flat, uniform distribution of radiation intensity over the seven fiber cores [Fig. 4(a)], translating into a Gaussian-shaped beam profile in the far-field [Fig. 4(b)]. Such an output beam profile remained stable over hours and no longer changed with the input conditions. To verify the spatial coherence of the SC outputs of individual PCF cores in different frequency bands, near- and far-field beam profile were measured using appropriate spectral filters. The output beam profiles were found to remain unchanged within the entire wavelength range from 600 to 1400 nm. The beam profiles in the visible regime were also recorded with a camera, as shown in Figs. 4(c) and 4(d). Increasing the pump power leads to a broader and relatively flat SC spectrum. A robust 5.4 W coherent SC output with a high spatial and spectral quality within the range of wavelengths from 500 to 1700 nm is generated [Fig. 3(b), blue line] under 11 W of launched pump laser with 80 fs pulse duration and a peak power up to around 3 MW. It is the highest power octave-spanning SC generated in PCF utilizing femtosecond pulses. The damage of the fiber input end prevented us from further power scaling. But it suggests a promising strategy to improve the output SC power. We believe that an appropriate fiber end postprocessing will enable further power scaling.

The temporal coherence of the generated 5.4 W SC is verified with the Michelson interferometer experiment.

Fig. 2. (Color online) Far-field beam profiles of the seven-core PCF output with a fiber length of 5 cm.

Fig. 3. (Color online) Spectra of the output SC for a fiber length of (a) 5 cm and (b) 20 m. Numerical simulations are shown by the dashed line. The inset of (a) shows the enlarged view of a normalized SC spectrum in the range from 730 to 800 nm.

Fig. 4. (Color online) Beam profiles of the seven-core PCF output with a fiber length of 20 m: (a) near-field and (b) far-field measured with beam analyzer; (c) near-field and (d) far-field images taken with a camera.
Clear and stable interference fringes appear both in the far-field [Fig. 5(a)] and near field [Fig. 5(b)]. The temporal coherence of the supercontinuum generated in different cores is also verified as shown in Fig. 5(c) with spatiotemporal superposition of pulses from four of the seven cores. We emphasize that, in Fig. 5(c), two time-delayed replicas of the pulse from the same core are recombined to give interference. In Fig. 5(c), however, the interference fringes appear because of the superposition of pulses from different cores. Such high power SC source with good temporal and spatial coherence is a powerful tool in science research.

These measurements visualize transition to an in-phase supermode regime of SC generation accompanying an increase in the fiber length. Alteration of incident pulses status or introducing an extra stress on the fiber, the phases in the cores are changed but quickly self-organized to the in-phase supermode. And the excellent beam profile is reproducible even if the fiber is recoupled. The input pulses average power is also varied from 5 mW to 11 W and the output beam profile remains almost unchanged as shown in Fig. 4. This indicates that the nonlinear refraction is not the responsible mechanism for phase self-synchronization [12]. In addition, the cores of the fiber are not doped with laser-active material, the gain effect is also not the dominant mechanism of coherence formation [13].

These results are also verified by our numerical analysis [cf. the dashed curves in Fig. 3(b)] based on the generalized nonlinear Schrödinger equation (GNSE) modified to include multiple fiber modes [14]. In this analysis, we neglect changes in the PCF modes induced by nonlinear-optical processes and represent the field inside the fiber as an expansion in the field-free modes of the multicore PCF. The spatial field profiles in these modes and their complex propagation constants were calculated using the finite-difference analysis [15]. With typical beat lengths of PCF modes (a few millimeters for 1.04 μm radiation) being much less than the fiber length, mode coupling effects play an important role in the nonlinear dynamics of ultrashort pulses. These effects are included in the model through the nonlinear terms of the multimode GNSE. The simulation results indicates that the strong coupling of the evanescent fields over long interaction lengths leads to the domination of the in-phase supermode [11,16]. As a result, the generated SC has a high spatial and spectral quality in an isolated fundamental mode of a multicore PCF.

In conclusion, we have demonstrated SC generation in a robustly isolated supermode of a seven-core PCF. With a femtosecond Yb-fiber-laser pump, the spectrum of the SC output of the multicore PCF spanned over more than an octave, stretching from 500 to 1700 nm. The output beam profile features a flat uniform distribution of radiation intensity over the seven fiber cores and translated into a Gaussian-shaped beam profile in the far-field. The high-quality beam profile is stable with respect to fluctuations of input laser beam parameters. Our experiments show that multicore PCFs offer a powerful tool for the generation of high-power SC.

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