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High energy femtosecond supercontinuum light generation in large mode area photonic crystal fiber

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A B S T R A C T

A large mode area photonic crystal fiber (LMA PCF) with an effective area of 180 μm^2 is used to generate a high energy, micro-joule range, flat, octave spanning supercontinuum (SC) extending from ~600 nm to ~1720 nm. A train of femtosecond pulses from a widely-tunable parametric amplifier pumped by a Ti:Sapphire regenerative amplifier system are coupled into a 20 cm length of LMA PCF generating a SC of 1.4 μJ energy. We present an experimental study of the high energy SC as a function of the input power and the pumping wavelength. The spectrum obtained at a pump wavelength of 1260 nm presents spectral flatness variation less than 12 dB over more than 1.1 octave bandwidth. The physical processes behind the SC formation are described in the normal and the anomalous dispersion regions. Our experimental results are successfully compared with the numerical solution of the nonlinear Schrödinger equation.

1. Introduction

A lot of effort has been dedicated to supercontinuum generation (SCG) in photonic crystal fibers (PCF) since 1999 [1,2]. This process occurs when intense light is coupled into such fiber and is characterized by the appearance of several new spectral components on both sides of the pump wavelength which gradually evolve to a wide continuum covering in some cases more than an octave span [3]. Most studies in this field have reported the SCG in a highly nonlinear photonic crystal fiber pumped in femto [4–9], pico [10,11], and nanosecond [5] regimes, with pulses of relatively low energy (pJ–nJ range). In most cases, small core PCF in which the dimensions of the core is about few μm^2 have been used, and the maximum coupled (and therefore output) power has been limited because of the high local intensity which can damage the fiber face. Large mode area photonic crystal fibers (LMA PCF) exhibit large core size with typically two orders of magnitude higher area and thus can support higher energy pulses delivered from the pumping laser. Besides, the larger dimensions of the LMA PCF facilitate the coupling into the fiber and in addition allow a better control during the fabrication process, eliminating the birefringence that can be introduced. The special properties of these fibers open the way to compact, single-mode, high energy supercontinuum sources with a low divergence of the output beam [12]. Few works only reported on the SCG in PCF LMA. Genty et al. studied the SCG by pumping 90–100 m long LMA PCF with 3 ns pulses [12]. Mitrofanov et al. obtained SC radiation in a 380 μm^2 LMA PCF spanning from 700 to 1800 nm with a total energy of 1.15 μJ [13]. In this paper we demonstrate that, a high energy supercontinuum of energy as high as 1.4 μJ and a flat spectrum extending from ~600 nm to ~1720 nm can be generated in 20 cm length LMA PCF. We present an experimental characterization of the properties of the supercontinuum generation in the LMA PCF at different input powers and pumping wavelengths. A train of 100 fs pulses of 28 nm spectral width resulting in a time-bandwidth product of ~0.54 at 1260 nm is used to generate the continuum. The pump source consists of a parametric amplifier pumped by a Ti:Sapphire regenerative amplifier system tunable from 1080 nm to 2600 nm at a repetition rate of 1 kHz. The fiber exhibits a zero dispersion wavelength (ZDW) at $\lambda_{ZDW}=1250$ nm and an effective area of 180 μm^2 at $\lambda=1260$ nm. A SC of a maximum energy of 1.4 μJ is generated into the fundamental mode of the fiber at $\lambda=1260$ nm, corresponding to a peak power at the fiber output of 14 MW. The physical processes leading to the construction of the continuum spectrum are studied by monitoring the growth of the SC while increasing the input optical power. The SC formation is investigated in both normal and anomalous dispersion regions. Our experimental results are successfully compared with the numerical solution of the nonlinear Schrödinger equation.

2. Fiber properties and SCG modelling

The fiber used in our experiment is a commercial Crystal-Fiber LMA PCF with a triangular lattice cladding having an effective area of ~180 μm^2. The effective area A_{eff} of the fiber was calculated by means

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of the finite element method (FEM). Our calculations were based on the scanning electron microscope (SEM) image of the cross-section of the fiber shown in Fig. 1 (a). The fiber nonlinearity $\gamma = 2\pi n_2/(\lambda A_{eff})$ is about $0.9\ W^{-1}.km^{-1}$ at $\lambda = 1260$ nm, where n_2 is the nonlinear coefficient of the pure silica. The cross sectional structure of the LMA PCF and its optical properties are summarized in Fig. 1 (a).

Fig. 1 (b) shows the calculated variation of the chromatic dispersion as a function of wavelength. The chromatic dispersion of the fundamental mode has been computed as a function of the wavelength in the range between 800 nm and 1500 nm by means of the FEM [14]. By taking $\lambda = 1260$ nm as the central wavelength of the input pulse, the calculated dispersion coefficient values of the Taylor expansion are: $\beta_2 = -3.1596\ ps^2/km$, $\beta_3 = 0.086016\ ps^3/km$, $\beta_4 = -0.00018106\ ps^4/km$, $\beta_5 = -1.3655e^{-7}\ ps^5/km$, $\beta_6 = 8.4181e^{-9}\ ps^6/km$, $\beta_7 = -6.923e^{-11}\ ps^7/km$, $\beta_8 = 3.2141e^{-13}\ ps^8/km$, $\beta_9 = -1.0015e^{-15}\ ps^9/km$, and $\beta_{10} = 2.177e^{-18}\ ps^{10}/km$.

In order to better understand the dynamics leading to the SC generation in our LMA PCF and predict the experimental parameters, we have performed a series of numerical simulations. The simulations are based on the extended nonlinear Schrödinger equation (NLSE) that is suitable for studying the evolution of pulses along the fiber axis z in a frame of reference moving at the group velocity of the pulse, $v_g = \frac{1}{\beta_1}$:

$$\frac{\partial U}{\partial z} = -\frac{\alpha}{2}U - \sum_{m\geq 2}\frac{j^{m-1}\beta_m}{m!}\frac{\partial^m U}{\partial t^m} + j\gamma\left(1 + \frac{j}{\omega_0}\frac{\partial}{\partial t}\right)x\left(U(z,t)\int_{-\infty}^{+\infty} R(t')\,|U(z,t-t')|^2 dt'\right). \quad (1)$$

a)

SEM image	Properties at 1260 nm	
	λ_{ZDW}	1250 nm
	γ	$0.9\ W^{-1}km^{-1}$
	A_{eff}	$180\ \mu m^2$
	Loss	0.01 dB/m
	Material	Pure silica

b)

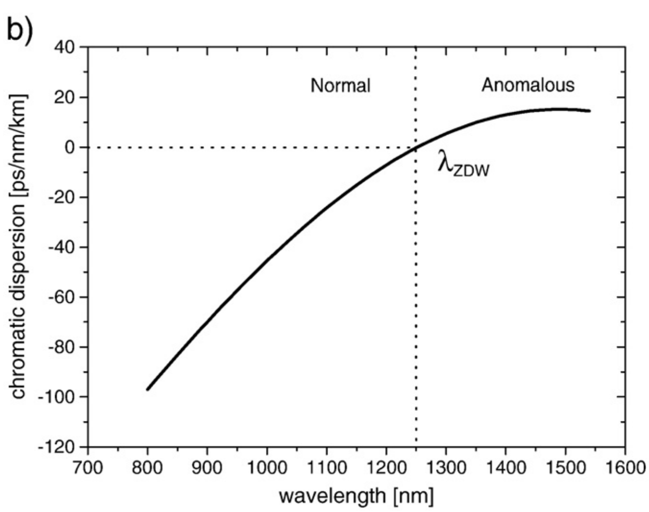

Fig. 1. a) Properties of the LMA PCF at $\lambda = 1260$ nm, b) Chromatic dispersion as a function of wavelength computed by means of the FEM.

In the above equation, U is the pulse envelope variation, α is the attenuation constant, β_m are the various coefficients in the Taylor series expansion of propagation constant β at the input pulse's central frequency ω_0 and γ is the nonlinear coefficient. The last term on the right-hand side of Eq. (1) describes the effects of self phase modulation (SPM) and Raman scattering; in particular, the time derivative takes into account self-steepening and shock formation. The Raman response function is given by: $R(t) = (1-f_r)\delta(t) + f_r h_r(t)$, where $f_r = 0.18$ and $h_r(t)$ is the Raman response function of the silica core: $h_r(t) = \frac{\tau_1^2+\tau_2^2}{\tau_1\tau_2^2}\exp(-t/\tau_2)\sin(t/\tau_1)$ with $\tau_1 = 12.2$ fs, $\tau_2 = 32$ fs [15]. Eq. (1) has been solved numerically by means of the split-step Fourier method with the fourth-order Runge–Kutta method for the last term [16].

3. Experimental results and discussion

3.1. Experimental set-up

The experimental set-up (Fig. 2) is based on a widely-tunable (1080–2600 nm) parametric amplifier (TOPAS) pumped by a Ti: Sapphire regenerative amplifier system delivering 100 fs long pulses at 1 KHz repetition rate. The maximum average power of the signal pulse generated by the TOPAS is 0.3 W (i.e. pulse energy of 300 μJ). Two steering mirrors (S_1 and S_2) are used to direct the laser beam and preliminary reduce the energy delivered from the TOPAS to below 50 μJ. A polarizer is used to finally control the input power injected into the LMA PCF. The beam is coupled into a PCF span of 20-cm length by means of an aspheric lens with a focal distance of 10 cm. A three-axis translation stage allows positioning the input cross-section with a resolution of 1 μm. With optimized coupling, a maximum light transmission through the fiber of about 10% was obtained, corresponding to maximum transmitted pulse energy of 1.4 μJ. The laser energy fluence on the input end of the fiber was about $0.1\ \mu J/\mu m^2$, remaining well below the damage threshold. The fiber is fixed at both ends and held straight in order to avoid bending losses. At the output end of the fiber the light is collected by a multimode fiber (MMF) connected to an optical spectrum analyzer (OSA) whose wavelength range is 350 to 1750 nm with a resolution of 1 nm.

3.2. Energy dependence of the supercontinuum

By propagating 100 fs pulses at a pump wavelength of 1260 nm, in the anomalous dispersion regime of the fiber, we observe a flat spectrum spanning from ~600 nm to ~1720 nm for an output energy at the fiber end of 1.4 μJ.

The physical processes leading to the formation of the supercontinuum were studied by monitoring the growth of the SC while increasing the input power. The resulting spectra are shown in Fig. 3, plotted on a logarithmic scale for different output energies. The insets show the far field patterns of the SC output.

As we are pumping close to the ZDW and in the anomalous dispersion regime, the mechanisms leading to the continuum in this case rely primarily on the processes of soliton fission and soliton-related dynamics. For low input energy (E = 0.02 μJ), we first note that the initial stage of propagation is dominated by approximately symmetrical spectral broadening (Fig. 3 (e)) but by progressively increasing the input energy (E = 0.05 μJ), we clearly see the generation and growth of distinct spectral peaks and structure on both the short- and long-wavelength sides of the input pump pulse. The long-wavelength peaks are associated with soliton pulses experiencing the Raman soliton-self frequency shift, whilst the generation of associated dispersive waves is responsible for the short wavelength structure in the visible region of the spectrum. For