Supercontinuum generation by higher-order mode excitation in a photonic crystal fiber

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Abstract: We describe an experiment in which a train of femtosecond pulses is coupled into a photonic crystal fiber (PCF) by means of an offset pumping technique that can selectively excite either the mode LP_{01} or LP_{11} or LP_{21}. The PCF presents a wide range of wavelengths in which the fundamental mode experiences normal dispersion, whereas LP_{11} and LP_{21} propagate in the anomalous dispersion regime, generating a supercontinuum based on the soliton fission mechanism. We find that the existence of a cut-off wavelength for the higher-order modes makes the spectral broadening asymmetrical. This latter effect is particularly dramatic in the case of the LP_{21} mode, in which, by using a pump wavelength slightly below cut-off, the spectral broadening occurs only on the blue side of the pump wavelength. Our experimental results are successfully compared to numerical solutions of the nonlinear Schrödinger equation.

OCIS codes: (060.5295) Photonic crystal fibers; (190.4370) Nonlinear optics, fibers; (060.5530) Pulse propagation and temporal solitons; (320.6629) Supercontinuum generation.

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1. Introduction

The development of highly nonlinear photonic crystal fibers (PCFs) has opened new horizons in the generation of wide-band supercontinuum radiation from visible to infrared by launching short pulses in a PCF length in the tens of centimetres range [1]. Unique dispersion characteristics and enhanced nonlinearity make the small-core PCF an ideal candidate for nonlinear applications. Supercontinuum generation (SCG) is a nonlinear optical phenomena characterized by a dramatic white-light spectrum [2]. Soliton effects, Raman shift and coupling with dispersive waves, modulation instability, four wave mixing (FWM), are the main effects leading to the generation of a broad spectrum starting from a narrow laser line. Since the first observation of SCG in PCF by Ranka et al. in 2000 [3], several experiments and numerical simulations were performed to investigate the dynamics of SCG in normal and anomalous regime [4-11]. Almost all the reported experiments were performed by exciting the fundamental fiber mode LP_{01} and observing SCG in the same mode. Ref.5 describes situations in which LP_{11} is predominantly excited, but the role of the cut-off wavelength is not discussed. In a few cases, third-harmonic generation [12,13] and four-wave-mixing [13,14] processes involving energy exchange among different modes were studied, but the efficiency of such processes is usually low because of unfavourable overlap integrals [13]. There are two reasons why the nonlinear propagation of higher-order modes is worth investigating. First, there is a wavelength range in which the LP_{01} mode propagates in normal dispersion, whereas higher-order modes experience anomalous dispersion [5,15]. Second, since higher-order modes present a cut-off wavelength above which the attenuation becomes very large, it is interesting to study how the cut-off may affect the growth of the supercontinuum.

In this work we describe an experiment in which a train of femtosecond pulses is coupled into a PCF by means of an offset pumping technique that can selectively excite either the mode LP_{01} or LP_{11} or LP_{21}. The PCF presents a wide range of wavelengths in which the fundamental mode experiences normal dispersion, whereas LP_{11} and LP_{21} propagate in the anomalous dispersion regime, generating a supercontinuum based on the soliton fission mechanism [4]. We find that the existence of a cut-off wavelength for the higher-order modes makes the spectral broadening asymmetrical. This latter effect is particularly dramatic for the LP_{21} mode, in which, by using a pump wavelength slightly below cut-off, the spectral broadening occurs only on the blue side of the pump wavelength. Our experimental results are successfully compared to numerical solutions of the nonlinear Schrödinger equation.

2. Experimental set-up and fiber properties

In our experiment the light source is a mode-locked Titanium Sapphire laser (Spectra-Physics Tsunami) emitting a 110-fs pulse train at the repetition rate of 80 MHz, tunable over the wavelength range 700-870 nm. A Faraday isolator, inserted to block the back-reflection from the input tip of the fiber into the laser cavity, broadens the pulse width up to 190 fs. The beam is coupled into a PCF span of 45-cm length by means of an aspheric lens having a numerical

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aperture of 0.65. The fiber is fixed at both ends and held straight in order to avoid bending losses. A three-axis piezoelectric translation stage allows positioning the input cross-section with a resolution of 20 nm. By moving the input tip of the fiber in the focal plane, we can exploit an offset pumping technique in order to excite selectively different fiber modes at the expense of the coupling efficiency: the higher the order of the mode, the lower the coupled power. At the output end of the fiber the light is collected by a 100x objective with a numerical aperture of 0.95. The spectral properties of the output radiation are monitored by an optical spectrum analyzer (Ando AQ-6315A) having a resolution of 0.1 nm. We also measure the total average power at the fiber output, which is only slightly smaller than the power coupled inside the fiber, considering that the linear attenuation coefficient of the fiber is about 0.3 m^{-1} in the investigated range of wavelengths.

The used PCF is made of fused silica and is fabricated using a standard stack-and-draw technique. The fiber cladding consists of a hexagonal lattice of holes with average diameter of 2.5 μm and pitch of 2.7 μm. The diameter of the solid core is about 2.2 μm.

We have performed a numerical study of the modal properties of the fiber by using a commercial finite-element-method (FEM) mode-solver. As input profile for the simulation we inserted a discretized scanning-electron-microscope image of the fiber cross-section. The calculated cut-off wavelengths of the LP_{11} and LP_{21} modes are, respectively, around 1300 nm and 830 nm. The dispersion curves of the three modes are shown in Fig. 1. The zero dispersion wavelengths are found to be 835, 665 and 600 nm, respectively. The spatial patterns of the three modes are shown in the insets of Fig. 1. The effective area of the three modes, calculated at 785 nm, is 3.46 μm^2 for the LP_{01} mode, 3.26 μm^2 for the LP_{11} mode, and 3.82 μm^2 for the LP_{21} mode.

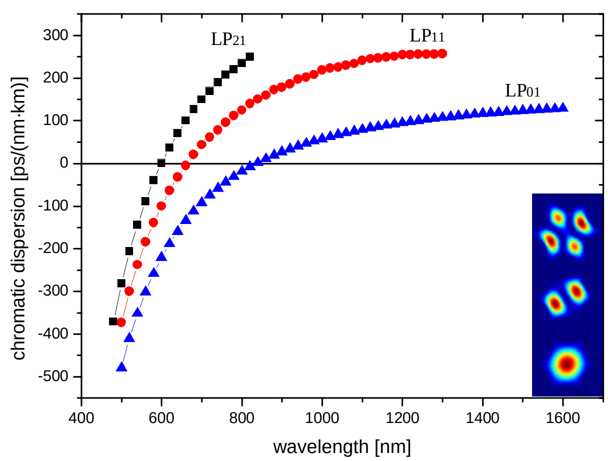

Fig. 1. Numerically calculated dispersion curves for the propagation modes of the PCF. Insets (bottom to top): fundamental, second and third order mode intensity distribution obtained by means of a FEM.

3. Results and discussion

The experiments were performed by changing both wavelength and average power of the fs-pulse train coupled inside the PCF, and detecting the optical spectrum and the average power of the output signal. For input wavelengths above 810 nm only the LP_{01} mode could be excited regardless of the positioning of the fiber in the focal plane. When the pump wavelength was tuned below 810 nm we were able to excite several modes. By choosing, by trial and error, the appropriate positioning of the fiber in the focal plane, the excitation turns out to be highly selective so that at the output of the fiber we can easily detect a single mode,

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either LP_{01} or LP_{11} or LP_{21}. In all cases we found that the spatial pattern at the output is unchanged even when the input power is increased to the point at which nonlinear interactions give rise to large spectral broadening.

The phenomena observed when the fundamental mode LP_{01} is excited are similar to those already reported in previous works [3-11]. We show in Fig. 2 the output spectrum observed with excitation at 790 nm and average power of 200 mW. The supercontinuum extends from 540 to 1430 nm.

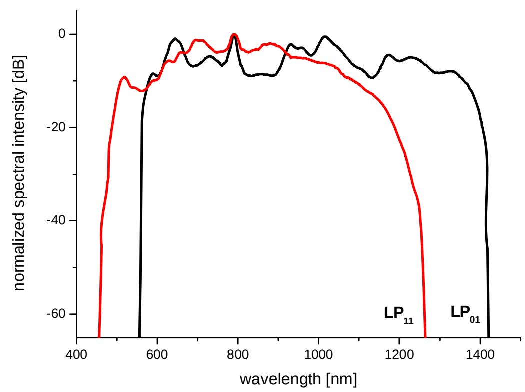

Fig. 2. Experimental output spectra for the modes LP_{01} and LP_{11} at 790-nm input wavelength and 200-mW average power. Note the effect of the cut-off wavelength on the LP_{11} spectrum.

The LP_{11} mode can be easily excited at input wavelengths lower than 810 nm, with a coupling efficiency comparable to that of the fundamental mode. Some output spectra are presented in Fig. 3. The inset shows the observed output spatial pattern. As the propagation occurs in the anomalous dispersion regime, soliton fission dynamics rules the spectral evolution [4,9,11,16]. The red shift of the Raman solitons is coupled to the emission of blue-shifted dispersive waves leading to the broadening of the spectrum on both sides of the pump wavelength. Consequently several peaks, appearing both in the visible and in the infrared range, characterize the spectral evolution. However it is important to notice that while the extent of the broadening towards the short wavelength side is comparable to the one observed with the fundamental mode, the generation of red-shifted spectral components stops at wavelengths shorter than 1300 nm with a progressive decaying intensity above 1100 nm. In Fig. 2 we compare the output spectra obtained by exciting the two modes LP_{01} and LP_{11} with the same input wavelength and similar coupled power, in order to show clearly the effect of the cut-off wavelength on the LP_{11} mode.

The fact that the observed broadening does not extend beyond 1300 nm is consistent with the value of the cut-off wavelength predicted by the numerical analysis. It remains unclear why we could not excite the LP_{11} mode by tuning the input wavelength above 810 nm.

The excitation of the LP_{21} mode is instead rather difficult. The focal spot of the pump beam has in fact to be critically positioned on the input cross section of the fiber far away from the point yielding the highest coupling efficiency. Such a strong offset severely reduces the amount of the power coupled into the fiber, in comparison with the LP_{01} mode and even with the LP_{11} mode. The maximum average power we can detect at the output of the fiber span is about 20 mW. The exact value could be slightly larger because of the limited collection efficiency provided by the objective. Figure 3 shows the output spectrum as a function of the average power. The inset shows the observed output spatial pattern. While the spectrum broadens down to the blue region, no spectral components on the long wavelength side are generated above 830 nm. Such a finding is consistent with the value of the cut-off wavelength derived from the numerical analysis. We also found that, even when the pump wavelength is tuned down to 705 nm, the spectral broadening is developed exclusively

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towards the shorter wavelengths except for an isolated low-intensity peak arising near 800 nm. It should be noted that, since the maximum power coupled into the mode is rather limited, we could not attain the situation in which the output spectrum becomes an almost flat supercontinuum.

The experimental results show that, notwithstanding the fact that spectral broadening on the long-wavelength side is not possible because the mode is not guided at wavelengths above 830 nm, still a considerable broadening on the short-wavelength side can be developed. Such a result is not obvious because the dynamics leading to continuum generation should imply some kind of coupling between red- and blue-shifted spectral components. As the input pulse experiences the anomalous dispersion regime, soliton propagation is expected to play a significant role in the evolution of the spectrum along the fiber. By progressively increasing the input power we can clearly monitor the generation and growth of blue-shifted peaks which can be ascribed to the emission of dispersive waves by soliton-like pulses. Even if the Raman-shift of these pulses is prevented, the perturbation they suffer because of the effect of higher order linear and nonlinear dispersion can generate the blue-shifted radiation.

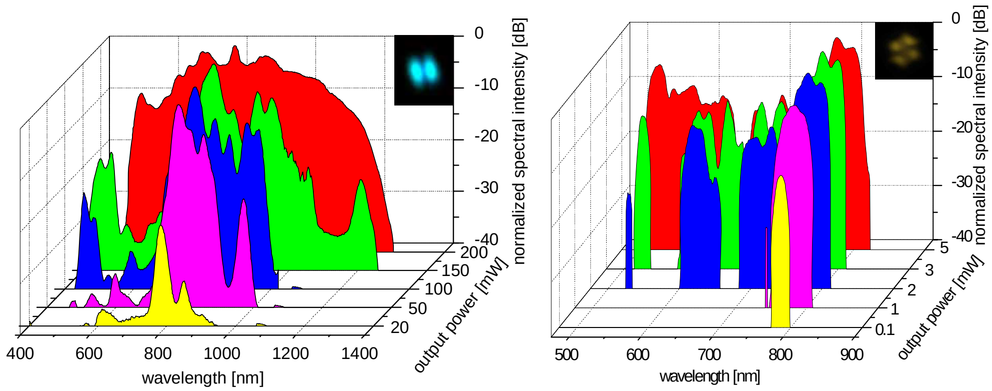

Fig. 3. Experimental output spectra for the modes LP_{11} (left) and LP_{21} (right) at the input wavelength of 790 and 780 nm respectively, for increasing output power. Insets: observed output spatial patterns.

We have carried out a numerical simulation of the pulse propagation in the fiber in order to verify our experim ental results and validate the proposed explanation. The numerical tool we have developed, as described in Ref.9, is based on the resolution of the nonlinear Schrödinger equation by the split-step Fourier method. In order to take into account the modal cut-off, the linear loss coefficient is made wavelength-dependent by using a very steep function (error-function) growing around cut-off from very low to very high values.

The numerical results we obtain are in fair agreement with the experimental data, as shown, for instance, by the comparison between simulation and experiment reported in Fig. 4 for the case of the LP_{21} mode excitation at 780 nm. Not only the visible continuum but all the main features of the experimental spectrum are reproduced such as the multi-peak structure arising around the pump wavelength, some secondary peaks, and the main peak close to 520 nm. In order to better clarify the mechanisms responsible for spectral broadening, we have also run the numerical simulation by excluding some specific terms of the nonlinear Schrödinger equation. The black curve shown in Fig. 4, designated as reduced numerical, is calculated by excluding the terms describing Raman and self-steepening effects. The fact that it describes pretty well the experimental results suggests that both those effects play a negligible role in the observed spectral broadening.

The numerical simulations clearly show that the impossibility for the spectrum to broaden to the red side does not halt the generation of a continuum on the blue side. In the usual situation the Raman-induced broadening of the spectrum to longer wavelengths increases the extent and the intensity of the continuum also on the blue side because of the resonant

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coupling between dispersive waves and red-shifted pulses. Even when the Raman shift is prevented by the fact that the propagation is forbidden because of the modal cut-off, there are processes responsible for the generation of new spectral components at higher frequencies. If the pump wavelength is tuned close to the zero dispersion wavelength, the simulation shows that the effect of higher-order linear dispersion is predominant.

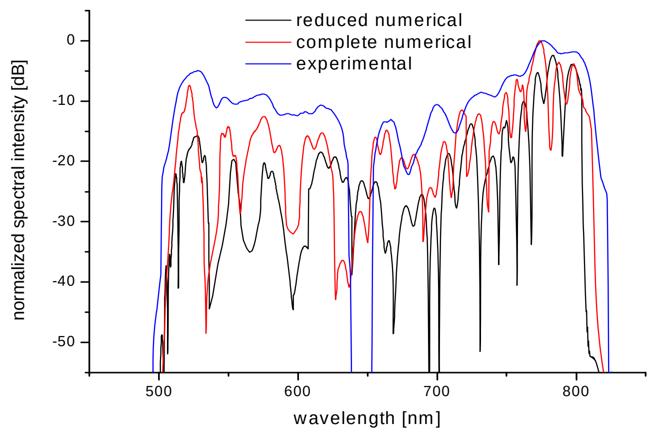

Fig. 4. Experimental and simulated output spectrum for the excitation of the mode LP_{21} at the input wavelength of 780 nm and average power of 5 mW. The black curve describes simulation performed by suppressing Raman and self-steepening terms in the propagation equation.

4. Conclusions

We have performed an experimental study of supercontinuum generation in a PCF by exciting selectively higher-order modes through an offset pumping technique. The properties of the PCF are such that there is a wide range of wavelengths in which the fundamental mode experiences normal dispersion, whereas the modes LP_{11} and LP_{21} propagate in the anomalous dispersion regime, generating, at sufficiently large input power, a supercontinuum based on the soliton fission mechanism. We find that the existence of a cut-off wavelength for the higher-order modes sets a limit to the spectral broadening on the long-wavelength side. This latter effect is particularly dramatic in the case of the LP_{21} mode, in which, by using a pump wavelength slightly below the cut-off wavelength, the spectral broadening occurs only on the blue side of the pump wavelength. Our experimental results are successfully compared to numerical solutions of the nonlinear Schrödinger equation. We note that the phenomena here described could be of interest also for the very recent line of research concerning supercontinuum generation in silicon nanowires [17].

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