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Modal four-wave mixing supported generation of supercontinuum light from the infrared to the visible region in a birefringent multi-core microstructured optical fiber

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ABSTRACT

We experimentally studied the process of supercontinuum generation in a birefringent multi-core microstructured optical fiber. By selecting the excitation of the fundamental mode, or by combining the first and the second order modes of a particular core, it was possible to emphasize the role of four-wave mixing on the transfer of power from the infrared to the visible region of the spectrum. We carried out an in-depth analysis of the effects of input light polarization on the generated supercontinuum spectral features. The measured polarization properties of the output Stokes and anti-Stokes bands confirmed the strong vector nature of the four-wave mixing processes. The experimental spectra exhibit excellent agreement with numerical simulations of the nonlinear mode interactions.

1. Introduction

Supercontinuum (SC) generation is a commonplace, but yet fascinating and in some aspects still unexplained phenomenon that is observed whenever high-power light waves are injected in a nonlinear medium (e.g. an optical fiber). Optical radiation gets spectrally broadened in a dramatic fashion as a result of the a complex interplay between linear and nonlinear responses [1]. In recent years microstructured optical fibers (MOFs) have been extensively used for the purpose of SC generation, as they enjoy high field confinement and large flexibility in the tailoring of the dispersion profile, so that the zero dispersion wavelength (ZDW) may be even shifted down into the visible range. In optical fibers SC is typically initiated by modulation instability (MI) of the quasi-continuous pump wave. The subsequent spectral broadening in the near infrared (NIR) is then ascribed to optical soliton formation and the associated Raman self-frequency shift. Whereas SC development in the normal dispersion regime and in the visible spectrum is associated with cross-phase modulation (XPM), four-wave mixing (FWM) with the corresponding NIR spectral components of the SC [2–8], or dispersive wave generation [9].

In spite of the extensive use of MOFs for research purposes, their applications to practical SC sources is until now limited by the maximum spectral brightness that can be obtained under single-core excitation (before the damage threshold of the fiber input end is reached). This observation motivates the interest in novel, high spectral brightness SC sources such as those based on multi-core MOFs. In principle, such fibers could lead to coherent/incoherent recombination of the SC that is individually generated by each core. As a first step in this direction, in this work we studied SC generation in a seven-core MOF. Note that the different geometries of the cores may lead to a substantial extension of the overall SC spectral range with respect to single-core MOFs. To this end, we characterized the spectral features of the SC that was obtained by individually exciting the different MOF cores. For symmetry reasons, it was sufficient to consider only three out of the seven cores. For this purpose we used a compact, low cost commercial nanosecond Nd:YAG Q-switched laser pump at 1064 nm. We performed a complete analysis of the SC characteristics as a function of the input pump polarization and power, as well as of the modal excitation conditions. Extensive comparisons between experiments and simulations provided a systematic analysis of the polarization properties of the generated SC light.

As a matter of fact, it was previously pointed out in Ref. [2] that modal FWM may lead to a bright visible SC. SC generation based on nonlinear interactions among different coupled fiber modes was also numerically analyzed in Ref. [10], where the propagation of femtosecond pulses in a holey optical fiber was simulated. To our knowledge, in our work we obtain the first experimental evidence

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of SC generation in MOFs under the simultaneous and efficient excitation on the two axes of birefringence of both the fundamental LP_{01} and the higher-order LP_{11} fiber modes (hereafter called intermodal vector excitation). As we shall see, under such pumping conditions the SC band-width could be substantially extended into the visible range of the spectrum. In addition, by using the input pump polarization degree of freedom we could obtain a nearly symmetric redistribution of the SC energy among the NIR and visible regions. In fact, vector FWM leads to three pairs of coupled sidebands in the NIR and in the visible that may provide a flexible shaping of the SC spectral broadening in each of their respective spectral regions.

This paper is organized as follows: In Section 2 we highlight the characteristics of the nonlinear multi-core MOF that was used in the experiments. In Section 3 we describe the experimental setup and the different SC generation results obtained when exciting the three representative cores of the seven-core MOF. A more detailed discussion is devoted to the case of central core excitation. Indeed, as we shall see, this configuration leads to the experimental evidence of intermodal vector FWM-activated SC. Our results are summarized in Section 4.

2. Characteristics of the microstructured optical fiber

Our multi-core silica fiber was manufactured by PERFOS, in collaboration with the XLIM Research Institute of Limoges, by employing the stack and draw technique. By using the Scanning Electron Microscope (SEM) image of the multi-core MOF (see Fig. 1) and a commercial electromagnetic field solver (COMSOL Multiphysics) we calculated the dispersion curves of the guided modes and could infer that the seven cores of the fiber were effectively decoupled. Each of the cores acted like an independent highly birefringent fiber.

We limit our analysis to the highlighted cores in Fig. 1: for symmetry reasons, their excitation leads to all types of SC that can be generated when using this fiber. We name these cores as "lateral", "central" and "off-axis" when moving from left to right in Fig. 1, respectively. The asymmetry created by the two central holes leads to highly birefringent lateral and central cores: their principal axes are parallel to the x and y directions. In fact, higher core ellipticity leads to higher values of phase and group birefringence [11]. The phase birefringence B_Φ is defined as the difference between the effective refractive indices of the two fundamental modes polarized along the x and y axes. Whereas the group birefringence B_g is the difference of their group indices. At the excitation wavelength of 1064 nm we obtain $B_\Phi = -1.7 \times 10^{-3}$ and $B_g = 2.7 \times 10^{-3}$ for the central core and $B_\Phi = -0.43 \times 10^{-3}$ and $B_g = 0.73 \times 10^{-3}$ for the lateral core, respectively. The off-axis core exhibits the relatively low phase and group birefringence $B_\Phi = 0.03 \times 10^{-3}$ and $B_g = -0.05 \times 10^{-3}$.

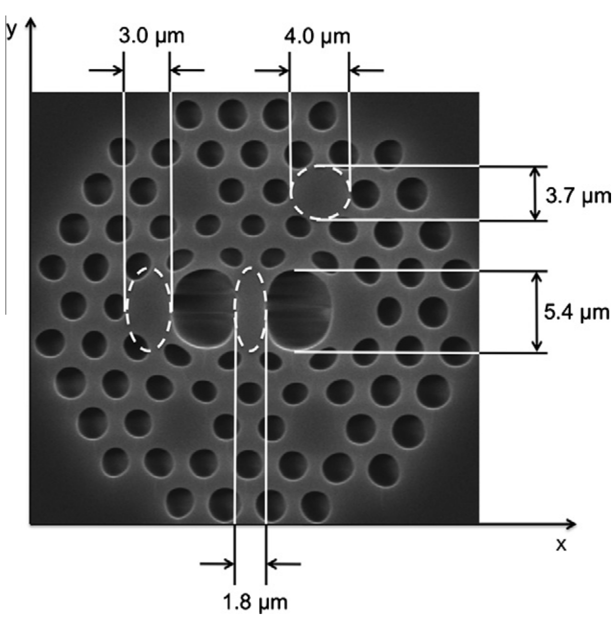

Fig. 1. SEM image of the MOF cross-section. SC generation was studied under excitation of the circled cores.

Four distinct modes are guided in the cores at the pump wavelength of 1064 nm, namely a fundamental LP_{01} and a second order LP_{11} mode oriented along each of the two principal birefringence axes. The dispersion curves of central core modes LP_{01} and LP_{11} with different polarizations are shown in Fig. 2. As it can be seen, for each and every core of the fiber propagation occurs in the anomalous dispersion region at the pump wavelength. By adjusting the vertical and horizontal position of the focused pump beam at the input face of the multi-core fiber it was possible to excite each individual mode in the different cores, as well as a mixture of different modes [12].

3. Experimental results

In this section we describe SC generation experiments using the multi-core MOF. We considered first the excitation of the off-axis core: in this case the pump spectral broadening is mainly due to pump MI-seeded self-Raman scattering. Next we considered the excitation of the lateral core: in this case a weak FWM process could be observed under certain launch conditions. Yet, no light in the visible range of the spectrum was generated when using this configuration. At last when exciting the central core we observed a broad continuum extending from visible to IR wavelengths originating from a complex interplay of efficient modal FWM, MI and Raman scattering.

In our experiments we used a Nd:YAG Q-switched laser pump delivering 600 ps pulses with 6 kHz repetition rate at 1064 nm. The peak power of the pump pulses was about 7 kW. Such type of pump was previously employed for SC generation using MOFs with a few micrometer core radius [2,13–16]. Different pump coupling efficiencies were obtained for each individual mode or mode combination. The coupled power into the fiber was measured by using a broadband power meter at its output. Fig. 3 provides a schematic of the experimental setup.

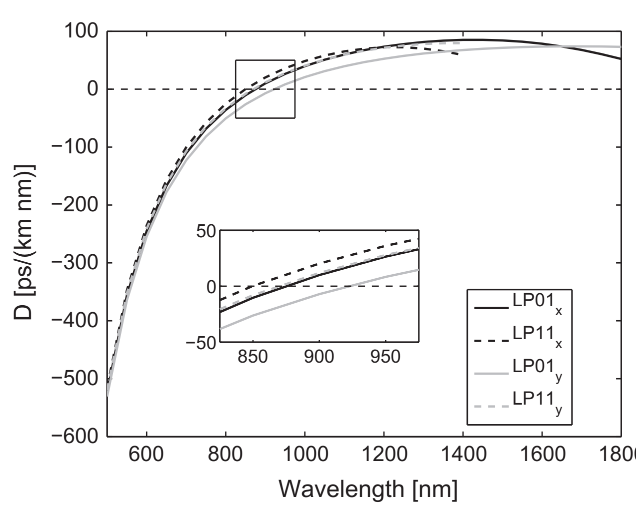

Fig. 2. Numerically calculated dispersion coefficients for the first two spatial modes of the central core of the MOF with a polarization state oriented along the two principal axes of the birefringence. The region around the mode ZDWs is magnified in the inset.