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Higher-order dispersion parameters management in highly nonlinear photonic crystal fibers for far-detuned frequency conversion

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Abstract: In this communication we present results dealing with the precise management of dispersion coefficients into two highly nonlinear fiber structures (a tapered PCF and an all-solid fiber) for far-detuned frequency conversion towards 2 μ m.

1. Introduction

Far-detuned frequency conversion by nonlinear processes in optical fibers is often used to significantly change the wavelength of a laser beam. A typical example is the frequency conversion from near-infrared (NIR) to mid-infrared (MIR) wavelengths by using four-wave mixing (FWM) processes in nonlinear optical waveguides. However, the efficiency of the parametric gain obtained with this nonlinear interaction is based on a very accurate control and therefore knowledge of the propagation constant (β) and associated derivative (β_i), notably the 2nd, 3rd and the 4th dispersion coefficients (noted β_2 , β_3 and β_4 respectively), as well as the zero-dispersion wavelength (ZDW) [1]. A precise control of these parameters at pump wavelength is then essential to ensure maximum conversion over a broadband wavelength range, especially when high detunings are targeted [1].

In this communication, we will present two techniques to precisely manage the chromatic dispersion and its associated higher order derivatives β_2 and β_4 by using specific highly nonlinear fiber designs. First, we will show how the use of a home-made tapered highly nonlinear PCF pumped at 1.03 μ m allows to extend the exploitable range of parametric gain over a spectral width of 200 nm around 2 μ m. In a second time, we will introduce a new design of all-solid highly nonlinear fiber for dual comb spectroscopy at 2 μ m.

2. Tapered HNL-PCF for broadband and tuned 2 μ m emission using degenerate four-wave mixing process

Our aim here is to numerically investigate d-FWM using a home-made tapered HNL-PCF to extend the exploitable range of parametric gain over a spectral width of 200 nm around 2 μ m. This is 5 times larger than the broadening which can be reached with the same un-tapered HNL-PCF. The proposed tapered fiber is based on small and continuous variation applied on the external diameter of the fiber during the drawing step (see Fig.1 (a)). The idea is to longitudinally change the dispersion properties brought by the fiber and seen by the pump radiation (close to 1.03 μ m) and then progressively shift the tuned signal wavelength. Therefore, we will accordingly cover a wide spectral range around 2 μ m. A numerical study has been carried out by solving the generalized non-linear Schrödinger equation (GNLSE) [2]. Fig.1 compares the numerical results from solving the GNLSE for the un-tapered HNL-PCF (Fig.1 (b)) and the tapered one (Fig.1 (c)). The input pulse considered in the model is at 1.03 μ m and comes from a 1 kW peak power, 50 ps full width at half maximum (FWHM), 10 MHz repetition rate laser source.

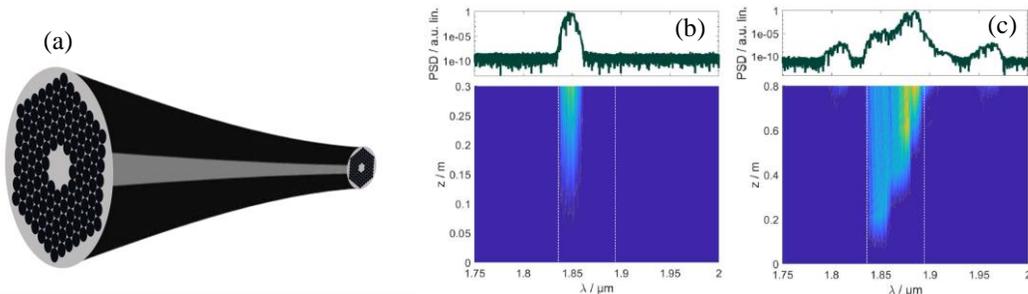


Fig. 1. (a) Schematic representation of the “tapered” HNL-PCF. Results from numerical simulations showing spectral evolution of the signal generated by d-FWM in (b) un-tapered HNL-PCF and (c) tapered HNL-PCF.

Fig. 1. (b-c) show that the bandwidth of the generated signal in a tapered HNL-PCF is widely improved by an order of magnitude compared to result using the un-tapered HNL-PCF. To experimentally validate the theoretical results, a tapered HNL-PCF has been fabricated (see cross-sections in Fig.2) and several long lengths of fiber pieces have been fabricated (0,5 m, 1 m and 2 m). by “linearly” varying the external diameter of the fiber from 140 to 132 μm (see Fig.2). Experimental study is ongoing, and results will be presented during the conference.

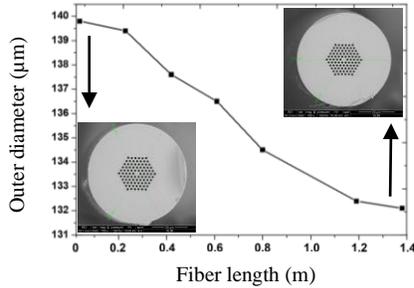


Fig. 2. Measured outer diameter along the tapered PCF for a fiber length of 1.4 m. MEB images of the cross-sections of the two ends of the tapered PCF are also shown (biggest core end on the bottom left and smallest core end on the top right).

3. New concept of an all-solid optical fiber enabling a precise control of the ratio β_2/β_4

In this section we propose a new design of an all-solid fiber that reconciles the accurate control of chromatic dispersion properties and the fabrication by standard stack and draw method, allowing a robust and reliable method against detrimental longitudinal and transversal fluctuations parameters during the fabrication process. The proposed concept relies on the discretization of the low-index trench of a conventional W-type HNL fiber (see Fig. 3). By doing so, one reduces the constraint imposed by the trench on the spatial electric field distribution of the guided core mode and therefore gets a thinner control over the mode spreading into the cladding as wavelength increases. Fig. 4 shows the impact of discretizing the trench into inclusions (ranging from 2 to 6) on the slope of ratio β_2/β_4 and on the ZDW position with respect to the diameter (noted “d”) of the low-index inclusions. To facilitate the comparison, results obtained with the standard W-type HNL fiber (including a low-index trench surrounding the core) are added in Fig. 4 (dark curve).

The near-IR frequency conversion in these fibers has been successfully demonstrated (see Fig. 4). We can see that the signal generated with the discretized HNL fiber (noted D-HNLF, see Fig. 4 (a)) is improved by one order of magnitude compared to the one obtained with the conventional W-type HNLF (see Fig. 4 (b)). This improvement can be explained by the well-controlled higher order dispersion coefficients, which is crucial for the FWM generation efficiency, in the D-HNLF compared to the W-type HNLF. We can also notice that the result obtained with the W-type HNLF exhibits Raman peaks, which are not present with the D-HNLF due to its large effective mode area. These preliminary experimental results are very encouraging and pave the way to the achievement of new generation of tunable laser sources.

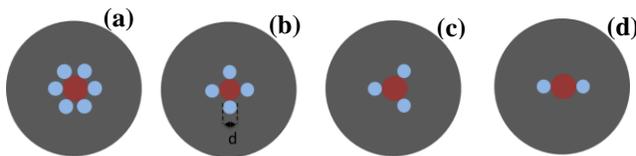


Fig. 3. New concept of fiber entitled D-HNLF in which the initial low-index trench is discretized into either (a) six low-n inclusions (6I), (b) four low-n inclusions (4I), (c) three low-n inclusions (3I) or (d) two low-n inclusions (2I). The core radius is fixed at 2.7 μm in all cases.

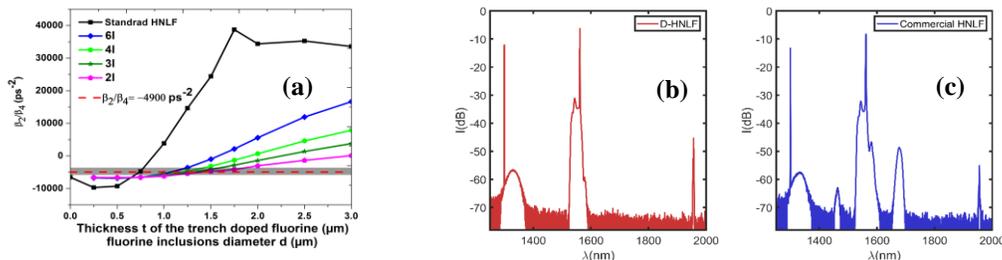


Fig. 4. Variation of (a) β_2/β_4 ratio calculated at $\lambda = 1.55 \mu\text{m}$. Blue, light green, dark green and purple curves correspond respectively to the case where the discretized trench consists in 6, 4, 3 and 2 low-n inclusions. The targeted values are highlighted by dashed red line. As a comparison, results obtained with the standard W-type HNLF are added in the graph (black curves). Experimental spectrum of the nonlinear conversion recorded at the output of a three inclusions D-HNLF (b) and of a conventional W-type HNLF (c) is presented.

4. References

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 [2] Dudley, John M. and Genty,” Supercontinuum generation in photonic crystal fiber” Rev. Mod. Phys 78, 1135-1184(2006).