Spatio-spectral analysis of supercontinuum generation in higher order electromagnetic modes of photonic crystal fiber

Benjamin Zwan,[1] Samuel Legge,[1] John Holdsworth,[1,*] and Bruce King[1]

[1]*School of Mathematical and Physical Sciences, University of Newcastle, University Drive, Callaghan 2308 NSW, Australia*

[*]*john.holdsworth@newcastle.edu.au*

Abstract: The far-field spatial distributions of higher order electromagnetic mode supercontinua were resolved spectrally and recorded. The supercontinua were created by precise control and direction of input pump energy offset axially from the photonic crystal fiber core. By processing the measured spectra, the spatial mode shape at each wavelength was determined. Discrete spectral features are associated with symmetrical spatial patterns arising from the host fiber geometry and suggest the electromagnetic mode pairing between the longer wavelength solitons and associated visible dispersive waves. Clear differences between supercontinua generated in fundamental and higher order electromagnetic modes exist. These data should inform theoretical studies as the solitons and the dispersive wave generated by fission may be matched by spatial orientation of the electromagnetic mode that both occupy.

OCIS codes: (190.3270) Kerr effect; (190.4420) Nonlinear optics, transverse effects in; (320.6629) Supercontinuum generation; (320.7140) Ultrafast processes in fibers; (190.4370) Nonlinear optics, fibers; (060.4005) Microstructured fibers; (190.5530) Pulse propagation and temporal solitons.

References and links

1. J. Dudley, G. Genty, and S. Coen, "Supercontinuum generation in photonic crystal fiber," Rev. Mod. Phys. **78**(4), 1135–1184 (2006).
2. G. P. Agrawal, "Nonlinear fiber optics: its history and recent progress (invited)," J. Opt. Soc. Am. B **28**(12), A1–A10 (2011).
3. S. Konorov, E. Serebryannikov, A. Zheltikov, P. Zhou, A. Tarasevitch, and D. von der Linde, "Mode-controlled colors from microstructure fibers," Opt. Express **12**(5), 730–735 (2004).
4. A. Efimov, A. Taylor, F. Omenetto, J. Knight, W. Wadsworth, and P. Russell, "Nonlinear generation of very high-order UV modes in microstructured fibers," Opt. Express **11**(8), 910–918 (2003).
5. Y. Vidne and M. Rosenbluh, "Spatial modes in a PCF fiber generated continuum," Opt. Express **13**(24), 9721–9728 (2005).
6. R. Cherif, M. Zghal, L. Tartara, and V. Degiorgio, "Supercontinuum generation by higher-order mode excitation in a photonic crystal fiber," Opt. Express **16**(3), 2147–2152 (2008).
7. N. Karasawa and K. Tada, "The generation of dispersive waves from a photonic crystal fiber by higher-order mode excitation," Opt. Express **18**(5), 5338–5343 (2010).
8. S. Legge, J. Holdsworth, and B. Zwan, "Supercontinuum generation in higher order modes of photonic crystal fibre," Proc. SPIE **8011**, 801146, 801146-6 (2011).
9. J. Cheng, M. E. Pedersen, K. Charan, K. Wang, C. Xu, L. Grüner-Nielsen, and D. Jakobsen, "Intermodal Čerenkov radiation in a higher-order-mode fiber," Opt. Lett. **37**(21), 4410–4412 (2012).
10. B. Kulmey, "CUDOS MOF Utilities," (2012). http://sydney.edu.au/science/physics/cudos/research/mofsoftware.shtml
11. J. M. Stone and J. C. Knight, "From zero dispersion to group index matching: How tapering fibers offers the best of both worlds for visible supercontinuum generation," Opt. Fiber Technol. **18**(5), 315–321 (2012).
12. S. Grafstrom, U. Harbarth, J. Kowalski, R. Neumann, and S. Noehte, "Fast laser beam position control with submicroradian precision," Opt. Comms. **65**(2), 121–126 (1988).
13. I. Cristiani, R. Tediosi, L. Tartara, and V. Degiorgio, "Dispersive wave generation by solitons in microstructured optical fibers," Opt. Express **12**(1), 124–135 (2004).

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1. Introduction

Much of the experimental and numerical work in the field of supercontinuum (SC) generation within photonic crystal fiber (PCF) focusses on the spectral and temporal properties of light from non-linear processes occurring during propagation of the fundamental electromagnetic (EM) mode in PCF [1,2]. Modeling based on a sound theoretical understanding of the underlying processes has successfully predicted the spectral properties of experimental supercontinuum generation in the fundamental EM mode ([1,2] and references therein).

Investigation of supercontinuum generation in the higher order EM modes within PCF, has revealed unique spectral and spatial features [3,4] not observed for supercontinua in the fundamental EM mode. Continuing work examined the temporal variation between modes [5], the spectral variation between supercontinua generated in different EM modes [6,7] and EM mode variation within a single supercontinuum [8]. A very recent paper [9] investigated the inter-conversion between modes in a few-moded solid core step index fiber excited at 1045nm and the possibility of energy interchange between these modes at 1120nm.

The Koronov and Cherif papers [3,6] detail the existence of a region between the zero group velocity dispersion (GVD) wavelengths for the fundamental mode and for the higher modes that will support soliton generation in only the higher order EM modes.

This work investigates this 700-850nm region with a technique that allows spatial and spectral characterization of the supercontinuum light emitted at the output of the PCF. The ability to offset pump the higher order EM modes by precise direction of the input laser into the PCF is central to this work as detailed below.

2. Experiment

The PCF (Thorlabs NL-850-2.8-02) was modeled to calculate dispersion and the group index of the fundamental and higher order modes using the CUDOS-MOF facility [10] as shown in Fig. 1. The 700-850nm region allows for solitonic behavior purely in higher modes while the group index differences will dictate the spectral characteristics of the resultant continuum [11]. The inset mode field representations show the limitations of the hexagonal close packed geometry of the model.

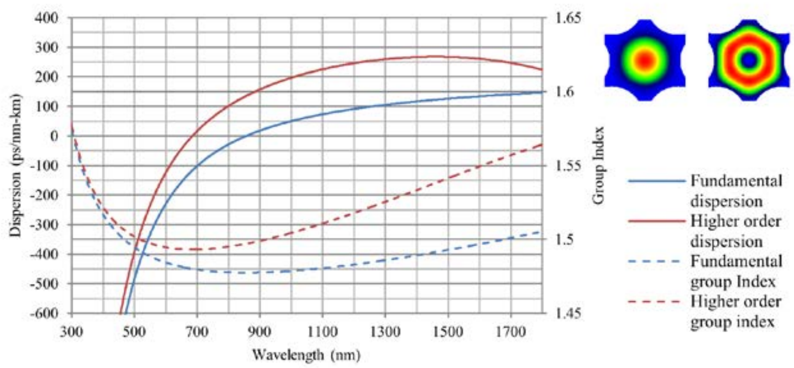

Fig. 1. Modeled PCF dispersion and group index.

Generating stable supercontinua in higher order EM modes requires the input laser beam be focused (*via* 2.00mm f.l. Thorlabs C150TME-B) onto the face of the PCF offset from the central axis of the fiber core and be held in position for extended periods of time. All results are generated in 0.75m of PCF. Two piezo-electrically controlled gimbal mounted mirrors are employed to control and stabilize beam position and angle, with quadrant detectors forming a feedback loop following the principles of Grafström et al. [12]. This gives sub-micron control

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of the location at which the horizontally polarized laser beam is focused onto the face of the PCF. Figure 2 details the experimental arrangement.

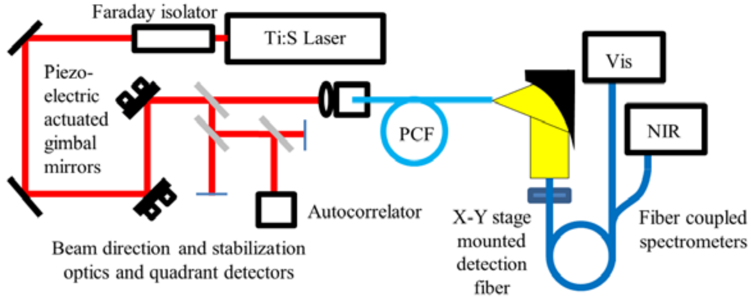

Fig. 2. Experimental arrangement for spatio-spectral measurement of supercontinuum.

This unique setup excites different EM modes by shifting the position and angle of the focused beam across the fiber core with nanometer precision. This is shown schematically in Fig. 3(a)-3(c), where pumping in the center of the core excites the fundamental mode Fig. 2(d) and pumping off axis excites higher order modes Fig. 2(e), 2(f). Figure 2(d)-2(f) are ccd recorded images of the integrated supercontinuum at the output of the PCF. There is evidence in Fig. 2(e) of both the fundamental mode and the higher mode being excited by the laser at input position Fig. 2(b) where the red dot is representative of the beam diameter. The data set recorded allows the spatial EM mode at each wavelength to be extracted and viewed.

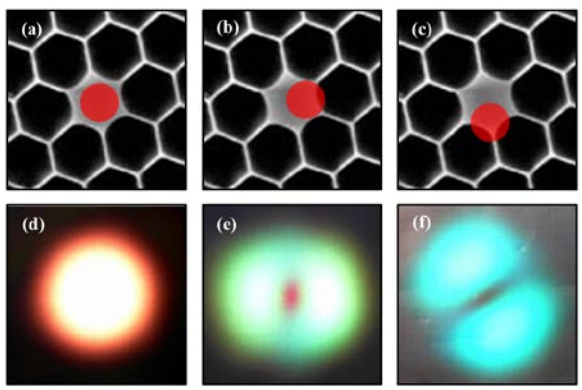

Fig. 3. Variation of integrated supercontinuum electromagnetic mode structures imaged with schematic of laser beam position on photonic crystal fiber core face. Higher order modes (e) and (f) result from offset fiber inputs (b) and (c).

Three axis differential screw microblocks served as coarse position adjusters at both ends of the PCF. The PCF output was achromatically expanded and collimated by reflection from an off-axis parabolic mirror (Fig. 2). A 400 μm diameter low OH silica core multimode fiber was raster scanned across the collimated supercontinuum far field over a 25 x 25 grid of spatial locations. The bifurcated output from the probe fiber was coupled to UV-Vis and NIR Ocean Optics spectrometers. A calibrated combined spectrum from 300 - 1600 nm was obtained at each of the 625 points on the raster grid.

3. Results and discussion

Very different supercontinuum spectra emerge from the PCF as the input beam position on the PCF core is altered. Figure 4 displays four measured spectra with the only difference being the position at which the laser beam strikes the input face of the PCF core. All other input parameters; the 200fs pulse duration; the center wavelength of 785nm and the 15nJ

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pulse energy were fixed. The insets of each plot show the visible light output of the PCF for each case integrated by the CCD array over all responsive wavelengths.

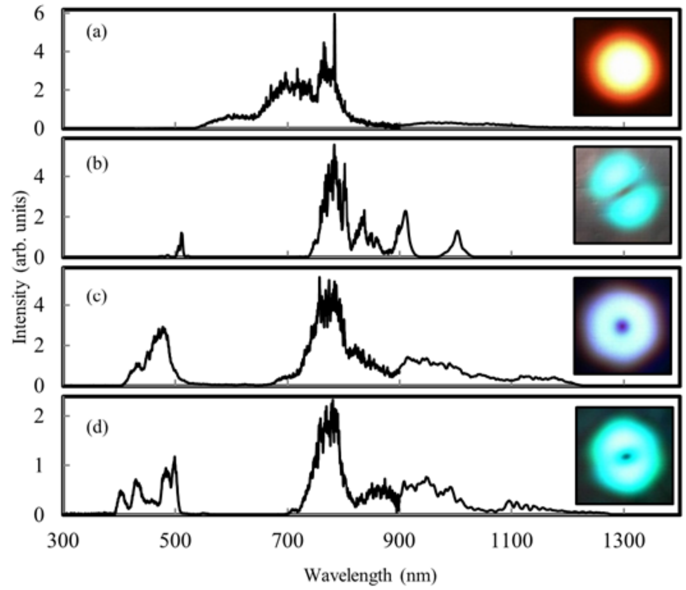

Fig. 4. Spectral variation of output supercontinuum and electromagnetic mode structures with position for identical input pulse duration, power and wavelength.

The striking differences between the spectra in Fig. 4 indicate that different processes dominate in the fiber. Supercontinua generated through solitons propagating in higher order EM modes, as in Fig. 4(b)-4(d), exhibit evidence that the input energy is coupling into lower order solitons, to produce dispersive waves and Raman self-frequency shifted solitons [1] upon fission resulting in discrete spectral features across the broadened spectrum and retaining the spatial mode properties. In contrast, the continuum generated by coupling into the fundamental EM mode, below the zero GVD wavelength Fig. 4(a), yields a spectrum broadened by non-solitonic third-order non-linear processes, where all wavelengths of light produced occupy the fundamental EM mode. Generating a supercontinuum in the fundamental EM mode above the zero GVD wavelength, Fig. 5 matches the expected, well documented [1,2], solitonic *and* third-order non-linear process broadened output, with all wavelengths propagating in the fundamental EM mode.

Figures 5 and 6 display the emission spectrum in blue for the UV-Vis spectrometer and in green for the NIR spectrometer with the spatial mode as measured at each of the wavelengths identified. The rich data set available from the experiment has a spatial result recorded for each pixel of the two spectrometer arrays between 300nm and 1600nm. The spectrum recorded at each raster point was an average of at least 6.56 million individual laser, and therefore supercontinuum, pulses.

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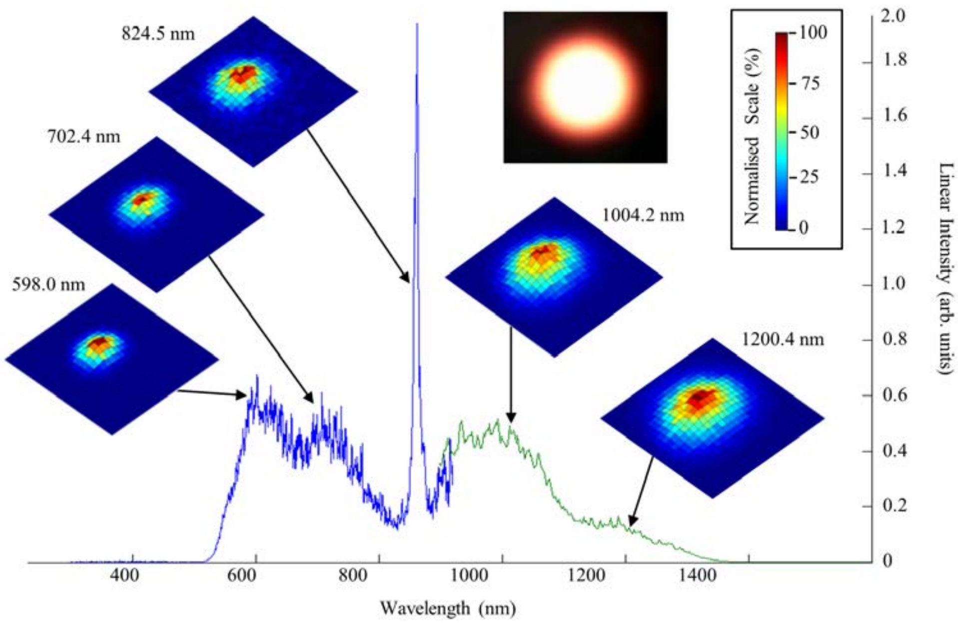

Fig. 5. Measured spectrum and spatial mode properties of a SC generated in the fundamental mode of Thorlabs NL-2.8-850-02 PCF using a 15nJ, 210 fs input pulse at 860nm, 10nm above the zero GVD wavelength. Inset is a visible camera image. The spectrum is representative of the broad continuous spectra characteristic of a fundamental EM mode generated SC in PCF.

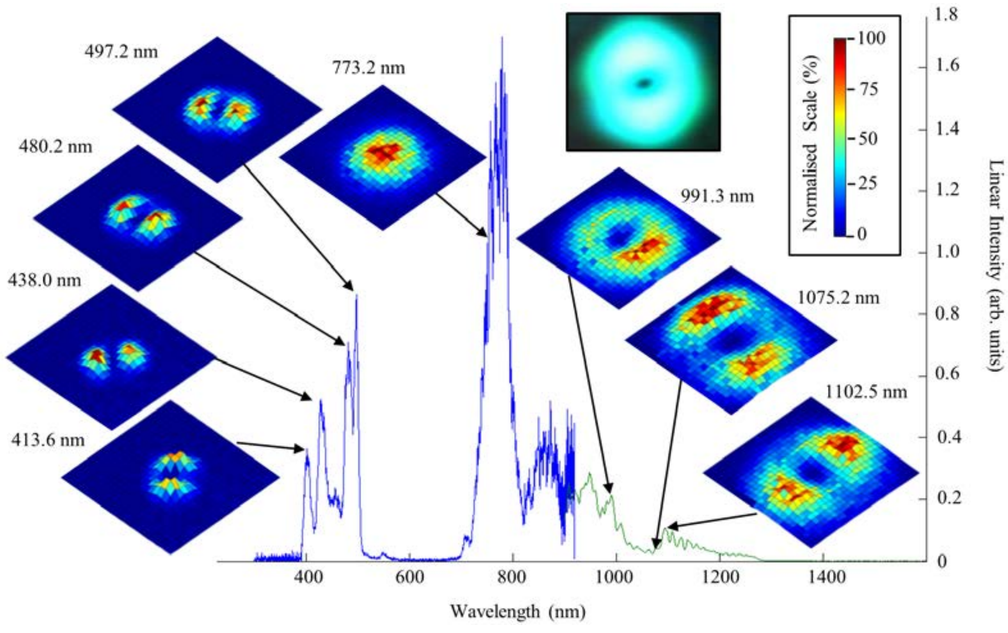

Fig. 6. Measured spectrum and spatial mode properties of a SC generated in the higher EM modes of Thorlabs NL-2.8-850-02 PCF using a 15nJ, 210 fs input pulse at 784nm, 66 nm below the fundamental EM mode zero GVD wavelength. Inset is a visible camera image.

The spatial mode structure of higher order EM mode supercontinua in Fig. 6 reveals a previously undocumented spectral complexity with six distinct dispersive wave peaks ranging from 400 – 550 nm generated using an input pulse wavelength of 784 nm. Cristiani et al. [13] proposed that each dispersive wave peak present in a supercontinuum output corresponds to a

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different fission event of a higher order soliton excited by the input pulse. With this interpretation, the spectrum in Fig. 6 reveals that the multiple peak features are characteristic of dispersive waves emanating from fission of lower order, possibly n = 2, solitons occupying higher order EM modes. Furthermore, it was found that light in each spectral peak in the 400-550nm region occupies a different, closely degenerate, higher order EM mode of the PCF as shown in Fig. 7. The dispersive wave may be matched to a parent soliton by EM mode.

Figures 5 and 6 correlate well with the group index matching as shown in Fig. 1 where the broadening of the fundamental and the higher order mode spread to equivalent points on the group index for the corresponding mode [11].

The different relative rotational position of the mode intensity lobes are a measure of the alignment of those modes relative to the structure of the fiber. As the fiber has hexagonal symmetry, or near to it, the expectation is that the fiber should support modes exhibiting this underlying symmetry. A detailed investigation of the spatial mode of identifiable peaks in the dispersive wave region matched the expected symmetry as shown in Fig. 7.

The discrete mode effective refractive indicies are not expected to cross over in the 800-1300 nm region so the coupling of light into the fundamental mode differs from Cheng [9] and is ascribed to the coupling coefficient for that mode based on the overlap between the input pump beam and the mode cross-section at launch.

The slightly larger mode dimensions in Fig. 7(d)-7(f) is the basis of the major axis postulate for these modes while the slightly smaller dimension of modes in Fig. 7 (a)-7(c) is consistent with the minor axis postulate.

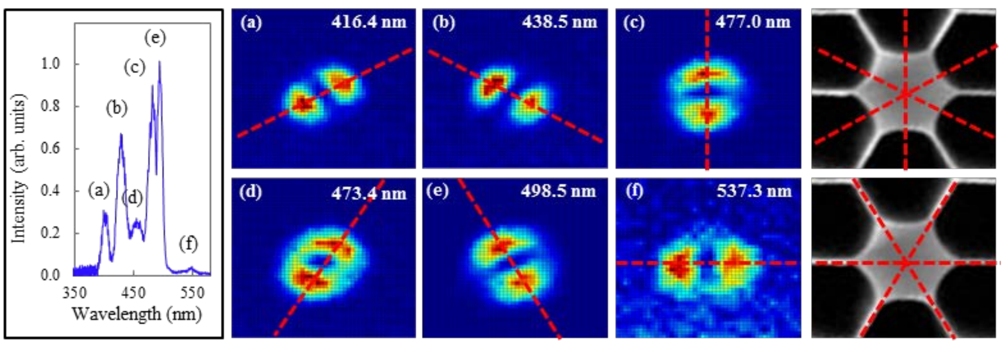

Fig. 7. Measured dispersive wave spectrum with peaks (a)-(e), measured spatial mode of each identified peak and postulated orientation of mode within the PCF core.

Note that these modes are not energetically degenerate. The higher order mode solitons are excited in discrete spatial orientations and, when undergoing fission, produce dispersive waves spatially aligned to their initial mode. Our postulate is that due to the imperfect fiber core geometry, that is, loss of hexagonal symmetry, the electromagnetic modes are not degenerate and thus the dispersive waves should appear at different energies.

4. Conclusion

The figures included above graphically convey new details of spatial mode features in supercontinua generated in higher order EM modes in PCF. Discrete spectral features are associated with symmetrical spatial patterns arising from the host fiber geometry and suggest the electromagnetic mode pairing between the longer wavelength solitons and associated visible dispersive waves. These data should inform theoretical studies and modeling of soliton fission and dispersive wave generation.

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