Supercontinuum generation in higher order modes of photonic crystal fibre

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ABSTRACT

Soliton behaviour in higher order electromagnetic (EM) modes in commercial highly nonlinear photonic crystal fibre (PCF) was investigated by mapping spatial and spectral emission. A femtosecond mode-locked Titanium:Sapphire laser was used to generate supercontinua within a set of higher-order electromagnetic modes by piezoelectric control of the spatial field input to the PCF. Coupling pump wavelengths within the normal dispersion regime for the fundamental EM mode into higher EM modes resulted in the emission of blue light, characteristic of higher order soliton fission, in higher order EM modes. Detailed spectral measurements across the spatial mode field output from the PCF, showed different spectral components of the generated continua occupying different spatial electromagnetic modes. In particular, the blue emission was found to be structured with spectral wavelengths at 440 nm and 450 nm associated with different spatial EM modes.

These new measurements are the first to detail high order solitonic interactions in higher order electromagnetic modes and to record different spectral emission wavelengths associated with different higher order spatial modes. These results are not well matched to current theoretical models for supercontinuum generation developed for the fundamental EM mode. The lower zero dispersion wavelengths associated with higher EM modes in PCF enable previously undetected engagement of these modes in supercontinuum generation and propagation.

1. INTRODUCTION

Soliton propagation and behaviour in highly nonlinear PCF is now a well researched area and the processes have been modelled and discussed in detail.[1] With few exceptions, this body of work has concentrated on the fundamental electromagnetic mode in the fibre waveguide.[2,3] Additionally, the usual approach to supercontinuum generation is to tune the incoming pump radiation to be well above the zero dispersion wavelength of the fibre so that the full range of solitonic and other non-linear broadening processes are engaged with maximum effect.

In this work, the wavelength region below the zero Group Velocity Dispersion (GVD) point for the fundamental EM mode supported by the fibre has been explored. Higher order EM modes were selectively excited in PCF in order to spatially and spectrally map the supercontinuum generated from pump wavelengths below the fundamental GVD zero.

2. MODELING

The spatial mode fields and dispersion of different EM modes in the PCF were calculated using a multipole method.[4,5] This method solves for allowed modes within a structured waveguide using a determinate minimisation procedure to find modes and their effective indexes. This method is limited as there is always the possibility that modes may be missed.
The dispersion of separate modes is determined by recalculating the effective mode index in small wavelength steps over the wavelength range desired and numerically taking the second derivative of index against wavelength using equation 1.

\[ D = -\frac{\lambda \frac{d^2 n}{d\lambda^2}}{c} \]  

(1)

Figure 1 shows the simulated fibre structure used in this method (representing Thorlabs NL-2.8-850-02 fibre). The resultant dispersion curves and their respective spatial mode profiles are shown in Figure 2.

![Figure 1](image1.png)

Figure 1. Simulated PCF structure (left) closely matching an optical image of illuminated experimental PCF (right) taken through a fibre microscope. This fibre has a pitch of 2.7 μm with the holes having a radius of 1.26 μm. The simulation uses circles to approximate the rough hexagonal shape of the holes in the real fibre.

![Figure 2](image2.png)

Figure 2. Calculated dispersion of the first three modes of the PCF. The images in the right show the mode field intensities for each of the calculated modes at 800 nm. Both the mode field profiles and the dispersion curves were calculated using CUDOS MOF Utilities.[4,5] The calculated fundamental dispersion matched well with the supplier’s specifications and experimentally observed modes follow the calculated intensity profiles. Top three modes have similar effective indices and the dispersion curves are nearly degenerate.
3. EXPERIMENTAL

The experimental setup as shown in Figure 3 details a femtosecond mode-locked Ti:S laser generating supercontinua within a set of higher-order electromagnetic modes by control of the PCF input spatial field. The direction of the incoming laser beam was stabilised and controlled via a piezoelectrically deflected mirror and a quadrant detector forming a feedback loop. The spatial output of the PCF was scanned using a motorised theta, phi mirror to direct the light towards a fibre coupled spectrometer. The input was sampled and recorded at each spatial grid point addressed by the theta, phi mirror scan.

![Figure 3. Experimental setup used to generate and scan the mode field output of the supercontinuum.](image)

The experimental setup and equipment used has certain limitations that affect the quality of the results. The piezo mirror feedback loop only has two axis of control and as such adjustment of laser input position on the fibre face resulted in a different angle of incidence into the fibre. The spectrometer used was also easily saturated by the intensity of the generated continuum making it difficult to take scans of the spatial outputs of the brighter wavelengths in the continuum. The latter is an annoyance and the former will be corrected with ongoing work in the laboratory.

4. RESULTS AND DISCUSSION

When the input wavelengths are in the range of 750 nm to 850 nm, a wide variety of continua outputs can be generated with varying spectral components in different EM modes by the initial coupling of the input light into different EM modes of the fibre. Results in Figure 4 are indicative of the complexity of the mode field generated with multiple wavelengths evident in a variety of modes simultaneously. These modes are of the correct spatial pattern to agree with the simulated modes in Figure 2.
Blue light, the characteristic emission of higher order soliton fission, is seen in Figure 5 and, was observed to be in higher order EM spatial modes when input wavelengths within the normal dispersion regime for the fundamental EM mode were coupled off axis into higher EM modes. In particular, the blue emission was found to be structured with spectral components at 440 nm and 455 nm associated with different spatial EM modes as shown in Figure 6.
These new measurements are the first to detail high order solitonic interactions in higher order electromagnetic modes and to record different emission wavelengths associated with different higher order modes. The current models for supercontinuum generation do not match these results well, as the focus of theoretical calculations and modelling has been almost entirely on the fundamental EM mode.

Figure 5 also shows a strong peak at 650 nm. While wave mixing processes are know to be common in continuum generation, the characteristic lower frequency peak that would be generated in a three wave mixing process is not apparent in this case. A hypothesis is that this light is part of the solitonic light that is generating the dispersive wave peaks seen at 440 nm and 455 nm. This hypothesis explains the lack of solitonic light seen in frequencies below the input wavelength, however the spectral range of this experiment only detected wavelengths up to 1100 nm allowing the possibility that the soliton has self frequency shifted past this wavelength.

It should be noted that if the peak seen at 650 nm is solitonic, it must exist in the 3rd order closely degenerate EM modes simulated in Figure 2 as the lower order EM modes have normal dispersion at this wavelength. This supports the hypothesis that the characteristic dispersive wave seen at lower wavelengths is in fact generated by solitons within the 3rd order EM mode as they show a clear higher order mode structure. The rotation of the 440 nm to the 455 nm peak can be explained by each wavelength propagating in the deferent but closely degenerate higher order EM modes. While this is a good explanation of the generation of the dispersive wave peaks, it leaves the process that generated light at 650 nm from the input wavelength of 745nm unexplained.

Further investigation is underway. A computational model that can incorporate interactions between EM modes within PCF is needed to begin to properly understand the experimental results that have been seen thus far.

5. CONCLUSION

This investigation into the supercontinuum generation in higher order modes has clearly shown that the nonlinear effects of PCF can be significantly altered by the coupling of light into the higher order modes in the fibre. It is clear that, as in the fundamental mode, the zero GVD point of these higher order modes plays a critical role in the generation of the blue light. These higher order modes allow soliton generation in regions of normal dispersion in the fundamental mode. This process allows for blue light generation mechanics of a supercontinuum to be observed while pumping in the normal
dispersion regime of the fundamental mode and highlights that regular fundamental mode supercontinua may couple into the higher spatial modes within a PCF fibre and undergo further solitonic processes within these modes.

REFERENCES


