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Near infrared transmission in dual core lead silicate photonic crystal fibres

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Photonic crystal fibres (PCF) can provide the high confinement needed to enable nonlinear optical processes to be studied in silicate fibre over short lengths without the need for large pulse energies. Additionally, the capillary stacking technique for PCF fabrication lends itself to the design of multiple core fibres and this capability has triggered much work into the properties of dual core PCF. In this paper, the effect of the dual core interaction on the nonlinear wavelength conversion is studied using a femtosecond oscillator in the near IR range. Effective supercontinuum generation in the range 1300–1700 nm is achieved in the anomalous dispersion regime.

Keywords: photonic crystal fibres, supercontinuum generation, soft glass.

1. Introduction

Photonic crystal fibres (PCF) are well known to provide the high confinement needed to enable nonlinear optical processes to be studied in silicate fibre over short lengths without the need for large pulse energies [1].

Pure silica based PCFs offer low attenuation over a large wavelength range and have been shown to be the perfect medium for various fibre sensors [2, 3] and active optoelectronic devices based on liquid crystals [4] as well as a very good medium for the study of nonlinear supercontinuum effects due to their very high confinement and long interaction length [5].

PCFs made of soft glasses cannot compete with pure silica PCFs in terms of optical attenuation, but they offer a much broader transmission window in the infrared [6], a higher refractive index and a much higher nonlinear refractive index [7]. As a consequence, mid-IR supercontinuum generation is possible in PCFs made of tellurite, heavy metal oxide and chalcogenide glasses [8–10].

The stack and draw technique for PCF fabrication lends itself to the design of complex structures such as fibres with nanostructured cores [11] as well as multiple core fibres [12–15]. This capability has triggered much work into the properties of dual core PCF for applications in nonlinear switching, frequency conversion and gain flattening [12, 13].

Multi-frequency generation in dual core fibres was initially described in [12] and the first prediction of the distinct advantages of multi-core PCF over single core in the context of nonlinear frequency conversion was given by BUGAR *et al*. [14] and further developed in [15]. The observed nonlinear properties were due to the complex nonlinear intermixing processes taking place in the dual core PCFs leading to an enhancement in the spectral content of the generated supercontinuum and opening new ways to control supercontinuum generation (SG). A drawback of this solution is the lower beam quality, which could potentially be an issue when coupling to standard single mode fibres.

In this paper, we study the effect of the dual core interaction on the nonlinear wavelength conversion using a femtosecond oscillator operating at 800 nm and an femtosecond OPA system operating at 1300 nm. The effects of core coupling and polarisation are investigated. This paper is a complementary study of the fibre presented previously in [15], where we focused on operation within the visible and near infrared ranges up to 1200 nm.

2. Modelling and development of dual core photonic crystal fibre

A two glass dual core PCF was fabricated using the stack and draw technique. The photonic structure of the cladding was made of the borosilicate soft glass NC21, developed in-house at ITME, whereas the cores were made from the commercially available F2 glass from Schott Corp. The fibre consists of three rings of holes arranged around the dual core. The material properties of NC21 glass are: refractive index $n_D = 1.518$, density $\rho = 2.50$ g/cm^3, coefficient of thermal expansion $\alpha_{20-300} = 82\times10^{-7}$ K^{-1}, glass transition temperature $T_g = 500$ °C and dilatometric softening point DTM = 545 °C. The oxide composition, transmission and viscosity properties of NC21 glass are shown in [14]. The nonlinear refractive index of the silicate glass NC21 is very close to that of pure silica [7]. The main advantage of NC21 is its excellent rheological properties and very good performance at low temperatures that allows the preparation of complex fibre structures. Since it is thermally matched to the high index F2 glass, dual glass fibres can be successfully developed with greatly reduced internal stresses.

As can be seen in the SEM images (Fig. 1), the core shapes are non-circular and of different sizes. The major and minor axes of the cores are 3.04 μm and 1.92 μm for the small core, and 2.42 μm and 1.78 μm for large core. The central air hole between the cores has a diameter of 1.69 μm. The cores were fabricated with different sizes to

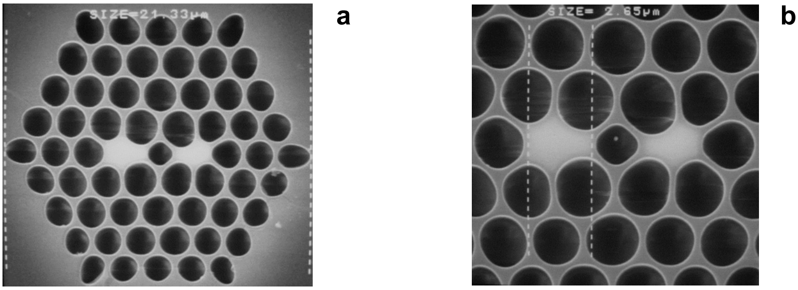

Fig. 1. SEM micrographs of the dual core photonic crystal fibre: photonic structure of the fibre (**a**); core area of the fibre (**b**). Light grey indicates area made of F2 lead-silicate glass, while dark grey area indicates an area made of low index NC21 borosilicate glass. Cores are intentionally different in size.

create dissimilar dispersion curves for four components of the fundamental mode. The lattice pitch Λ in the fibre was 2.29 μm while the filling factor d/Λ in the photonic cladding equalled 0.91. The overall diameter of the photonic structure was 21.33 μm.

The modal and dispersion properties as well as the effective mode areas of the fibre were calculated with a finite difference method based on the real structure taking into account the dispersion of the bulk glass by means of Sellmeier coefficients.

The fundamental mode of the dual core PCF is composed of four components that differ in electrical field symmetry (even and odd) and in polarization (along main axis).

The calculated phase birefringence is $B = 0.2\times10^{-3}$ and $B = 0.7\times10^{-3}$ for both pairs of components with a similar type of symmetry in the electrical field. The calculated effective mode area for every component of fundamental mode was 6.3 μm^2. The zero dispersion wavelength (ZDW) was calculated to be 1.22, 1.37, 1.38 and 1.51 μm for the four components of the fundamental mode (Fig. 2). The obtained dispersion does not allow the use of a femtosecond Ti:sapphire oscillator in the range of 750–900 nm to pump in the anomalous dispersion region as was shown in our previous paper [15].

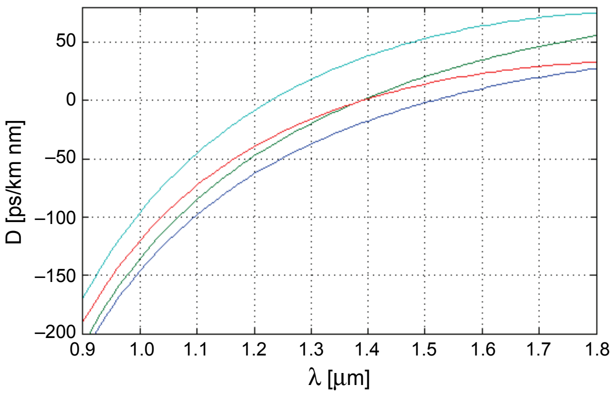

Fig. 2. Dispersion characteristics for the four components of the fundamental mode of the dual core photonic crystal fibre.

3. Near infrared transmission properties

The linear transmission properties of the fibre were studied in the third telecommunication window. An amplified spontaneous emission (ASE) source based on erbium doped fibre was used as a broadband source in the spectrum range 1550–1580 nm. The following schematic (Fig. 3) depicts the setup used. A small core silica fibre (Sumitomo HNLF Φ 3.5 μm) was used to butt-couple to the test fibre. A set of two micropositioners with submicrometer precision allowed highly efficient coupling into the test fibre cores and selective collection of the signal from the core area without scattered light in the fibre cladding. A test sample 50 cm long of the dual core PCF was used for tests.

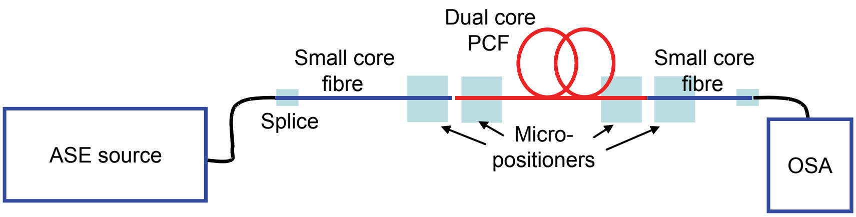

Fig. 3. Schematic of setup used to study near IR transmission.

The output modes for different launch conditions are shown in Fig. 4. The inner cladding tube in which the capillaries are stacked during fabrication can be seen in Figs. 4**a** and 4**b** as these structures guide the cladding modes and can act as multimode waveguides when the input fibre is offset from the core region. When input light is properly aligned against the test PCF all of the incident light can be effectively coupled into both cores as shown in Fig. 4**c**. Energy transfer into cladding was not observed in this case.

The transmission spectrum for both the ASE source and the light transmitted through the PCF fibre were recorded and shown in Fig. 5. This spectrum was observed

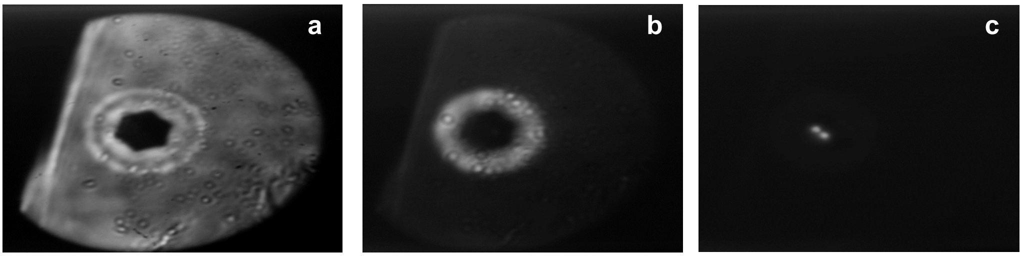

Fig. 4. Near field images of the photonic crystal fibre output under different coupling conditions at 1550 nm: light is coupled into fibre cladding (**a**), light is coupled into inner cladding tube in which the capillaries are stacked during fabrication (**b**), light is coupled into both cores (**c**).

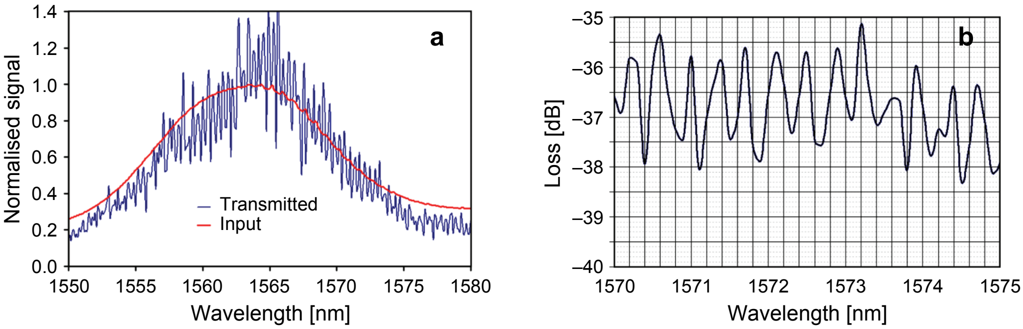

Fig. 5. Normalised ASE transmission before and after the dual core fibre (**a**). The modulation from inter core coupling is shown in (**b**).

for the case where the output from one core is collected for a single core excitation. The spectral modulation results from a combination of the inter core and polarization mode coupling.

Attenuation of 6.7 dB/m for the PCF was measured using cut back technique at 1550 nm. This is typical attenuation possible to achieve in PCF made of silicate glass. It limits practical use of this type fibre up to a few tens of centimeters and determines its application to some specific purposes as nonlinear medium.

4. Propagation of femtosecond pulses in dual core PCF

A schematic of the system used to study femtosecond pulse propagation in the dual core fibre is given in Fig. 6. Microscope objectives with high numerical aperture (NA = 0.65) were used to generate the spot sizes required to excite each core separately. The linear polarisation of the optical parametric amplifier (OPA) source was adjusted using a half-wave plate and the output spectra were recorded using a multimode silica fibre coupled to a USB spectrometer.

The signal output from the OPA was tuned to 1330 nm and the transmitted spectra were recorded for a 500 nJ incident pulse energy for a 18 cm section of

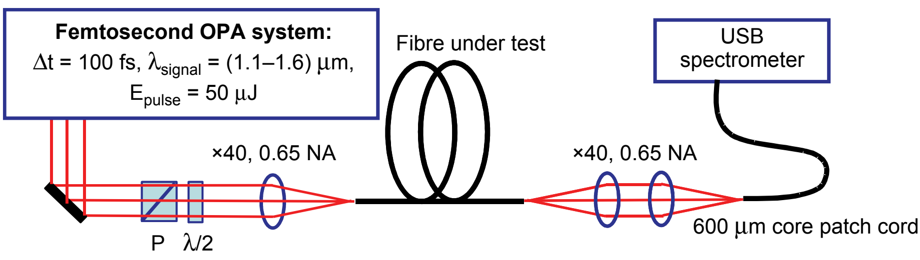

Fig. 6. Experimental arrangement for femtosecond pulse propagation measurements.

the dual core PCF. The coupling efficiency was estimated to be 40%. The amount of broadening observed was optimised by rotating the half-wave plate, since the PCF is birefringent and the polarization components of fundamental mode possess different dispersion characteristics. Spectra are shown for the wave plate angle producing the largest extent of continuum and also the polarisation orthogonal to this (Fig. 7). The dependence was found to be greater in the larger core and corresponds to the higher birefringence present in this core.

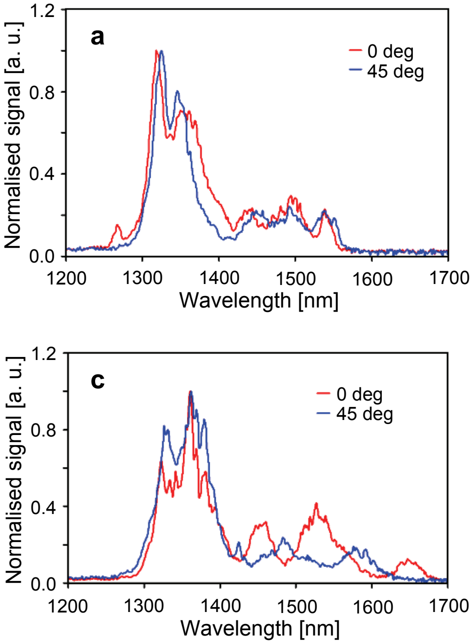

Fig. 7. Nonlinear spectral broadening and wavelength generation in dual core fibre for different angles of the half-wave plate for coupling to the small (**a**), large (**b**) and both (**c**) cores.

The collated spectra are shown on a log scale in Fig. 8. At this energy and fibre length, there appears to be little improvement in the extent of the continuum when coupling to either the large or both cores simultaneously whereas coupling to the small core produces significantly less broadening. This is thought to be due to a decrease in the coupling efficiency to this smaller core in a manner similar to that observed previously when the dual core fibre was excited at 806 nm [15]. In this case, however, the general character of spectrum is different. We can identify several separate peaks and a very asymmetric spectrum with respect to the pump wavelength shifted into the longer wavelength regime. This is typical of the spectrum that might be observed during soliton generation when the fibre is pumped in the anomalous dispersion regime [5].

The generated spectrum had a bandwidth of 400 nm red shifted with respect to the pump wavelength. However, further simulations have shown that the registered

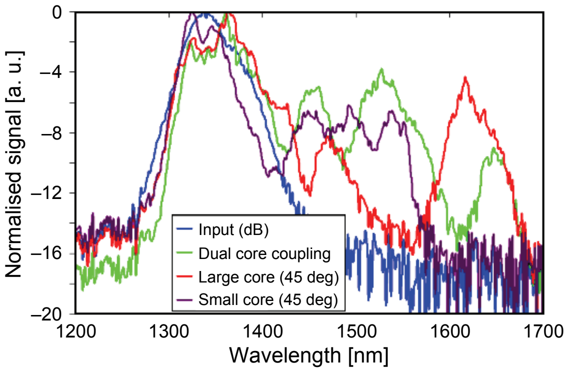

Fig. 8. Normalised output spectra for three launch conditions with input spectrum shown for comparison.

spectrum is limited to 1700 nm due to the sensitivity limit of the USB spectrometer, not the generated spectrum (Fig. 9).

To confirm the solitonic origin of the spectral broadening we numerically investigated SG in the dual core PCF by solving numerically a nonlinear Schroedinger equation (NLSE) with the split step Fourier method implemented by TRAVERS *et al.* [16]. For this set of simulations we considered all four components of the fundamental mode

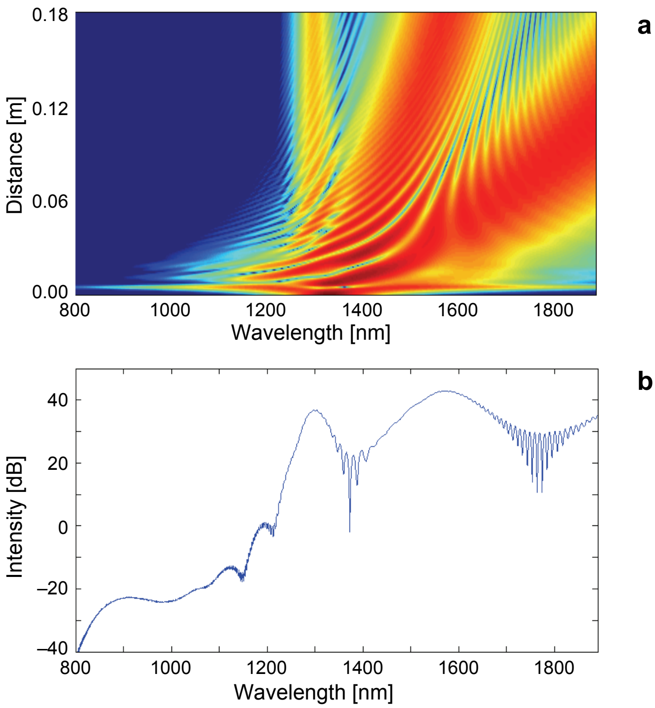

Fig. 9. Propagation of 100 fs pulse in 18 cm long dual core fibre (**a**), spectrum broadening at the distance of 18 cm (**b**).

and introduced an optical pulse with a pump wavelength of 1330 nm, a pulse length of 100 fs and total pulse energy 200 nJ. Three of four components of the fundamental mode have normal dispersion at pump wavelength (Fig. 2). The obtained broadening is symmetric and narrow since self phase modulation is the dominant nonlinear mechanism in this case. These components are responsible for the symmetric broadening of the peak related to the pump wavelength at 1330 nm. The fourth component of the fundamental mode with ZDW = 1220 nm is responsible for the large non-symmetric broadening. Simulation results for this component allow the identification of the generation of two solitons. We observe a red shift of their intensity peaks during propagation in the fibre (Fig. 9**a**) and have calculated that the two main peaks lie at 1566 nm and above 1900 nm. Similar results were observed in the experimental results when the large core was excited (Fig. 8), although the soliton peak was at 1620 nm in this case.

The agreement between simulation and experiment is not perfect for several reasons. Firstly, the numerical solution of the nonlinear Schroedinger equation is performed for a single dispersion characteristic, while in the experiment all four components with different dispersion characteristics contribute to the spectrum generation [16]. Moreover, some additional errors are introduced by the estimation of the nonlinear coefficient and the attenuation of the fibre as well as the peak power of the pulse coupled into fibre's core. The simulations do provide a qualitative explanation of the origin of the observed spectral broadening and allow an approximate prediction of the generated spectral bandwidth.

5. Conclusions

The transmission properties of a dual core photonic crystal fibre fabricated with a lead silicate glass have been studied in the near infrared range. The inter core coupling has been confirmed by observing the transmission of a broadband source. Supercontinuum generation in the anomalous dispersion regime is observed under illumination with a 100 fs pulse at 1330 nm. The effects of incident polarisation on the nonlinear spectral broadening have been introduced.

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