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Tailoring the Nonlinear Response of Hollow-core Photonic Bandgap Fibres

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Abstract. We have fabricated 7-cell and 3-cell core hollow-core photonic bandgap fibres with core sizes ranging from ~ 16 μm to 6.5 μm. A numerical study of the nonlinear coefficient of fibres with different core sizes is carried out. We show that the nonlinearity is more effectively increased by a 3-cell core design than by reducing the size of a seven-cell core.

Keywords: Photonic bandgap fibers, hollow-core waveguides.
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INTRODUCTION

In a photonic bandgap fibre light can be trapped in a hollow-core thanks to a synthetic photonic bandgap material that surrounds the core [1]. For wavelengths within the bandgap formed in the cladding, light introduced into the core mode is unable to escape through the surrounding cladding material. It is therefore well confined to the core and can be guided with low attenuation. Outside the bandgap the light spreads out into the cladding and is lost.

Over the past decade, hollow-core photonic bandgap fibers (HC-PBGFs) have been developed from a radical concept to a high-performance product. Indeed, fibres with very low attenuation – well below than 20 dB/km at 1550 nm wavelength - are readily available. Such low attenuation values have enabled the use of HC-PBGFs in a wide range of applications [2,3] and recently there has been a growing interest in fabricating novel HC-PBGFs with particular modal properties. For example, we have reported a fibre with increased bandwidth, reduced dispersion and reduced dispersion slope compared to previous designs [4], M.N Petrovich *et al* fabricated a single mode fibre based in a 3-cell core design [5], and B. J. Mangan *et al* reported on a low-loss highly birefringent fibre [6].

HC-PBGFs present a much lower nonlinearity (~3 orders of magnitude less) than any solid core fibre. Their low nonlinearity combined with their dispersion properties make them ideal for the delivery and manipulation of ultrashort pulses [7-9]. These emerging applications will benefit from the development of fibres with tailored nonlinear response and dispersion properties. By changing the core size of the fibers while adjusting the cladding parameters to keep the same operational wavelength it is possible to modify the overlap of the mode with the cladding structure and therefore modify the nonlinear response. In this paper we present 7-cell and 3-cell core HC-PBGFs which core diameters in the range ~16.7 μm to 6.5 μm and discuss how their nonlinearity and dispersion can be tailored for the manipulation and propagation of high-energy pulses.

In this paper, the nonlinear response of idealized 7-cell and 3-cell core fibres is numerically analyzed. The nonlinear coefficient of the 3-cell fibre is 6.5 times larger than that of the 7-cell fibre, which is in agreement to the results in [4]. The mode of the 3-cell fibre extends more into the cladding structure, therefore the contribution from glass to the total nonlinearity is larger than that from air. In contrast, for the 7-cell core the major contribution to the nonlinear coefficient comes from air. Finally, variations in the nonlinearity of 7-cell fibres due to changes in the cladding structure are analyzed.

7 CELL CORE AND 3 CELL CORE PHOTONIC BANDGAP FIBRES

The fibres presented here have been fabricated using the stack-and-draw technique as described in [4]. The core has been formed by simply omitting the 7 or 3 central capillaries in the initial stack. During the final draw stage, the core can be expanded or compressed from its initial size by controlling the pressure applied in it. Scanning electron microscopy (SEM) images of a fabricated 7-cell core and two 3-cell core fibres with different core sizes are shown in Figure 1(a,b,c). Observed near field profiles recorded at 1600 nm are also shown for each fibre. All fibres incorporate a thin core/cladding interface, which reduces the impact of surface modes in the guidance [4]. The pitch (Λ) of the 7 cell fibre is ~ 5.2 μm while that for the 3 cell fibers is Λ ~ 3.7 μm. The core diameter of the 7 cell fibre is ~16 μm while for the 3-cell fibre in Figure 1(b) 10 μm and 6.5 μm for the fibre in Figure 1(c). Due to its smaller core and higher mode overlap with the glass (as clearly seen from the mode profiles in Figure 1), the 3 cell fibres are expected to present a much higher nonlinear coefficient than the 7-cell fibre.

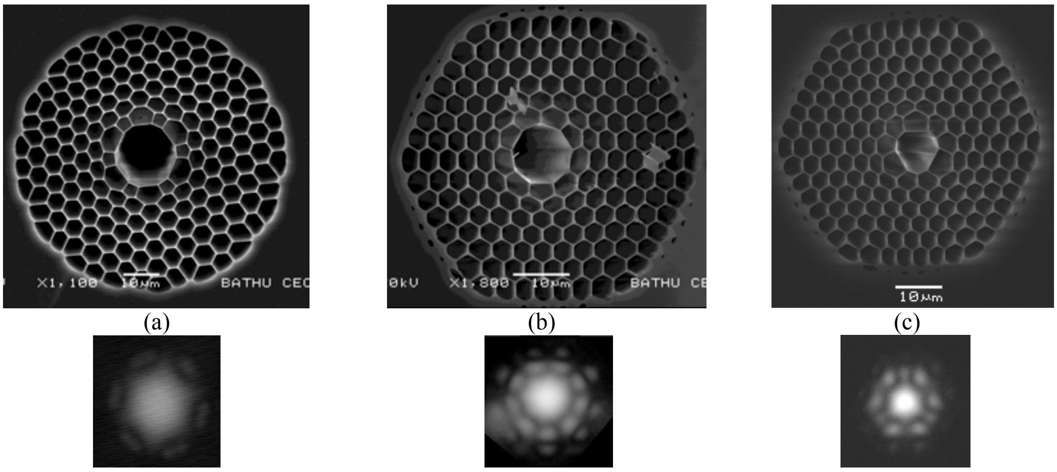
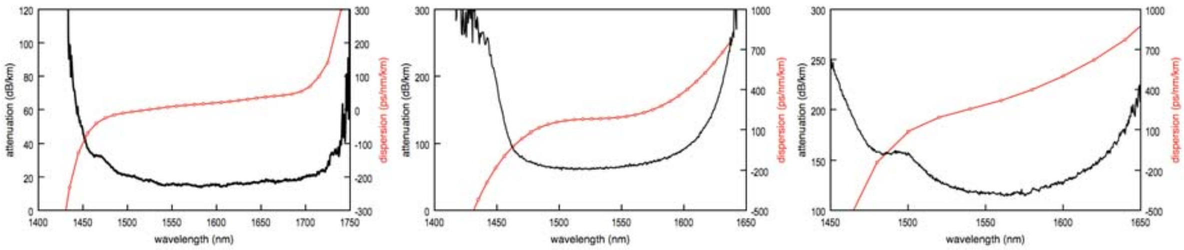


FIGURE 1. SEM micrographs of HC-PBGFs designed to operate at 1550 nm and near field images of the fundamental core modes recorded at 1600nm. (a) 7-cell core diameter 16.7 μm, (b) 3-cell core diameter 10 μm, and (c) 3-cell core 6.5 μm.

The optical attenuation together with the group velocity dispersion (GVD) of the three fibres is shown in Figure 2. The minimum attenuation of the 7-cell fibre is 15 dB/km Figure 2(a), while the 3-cell fibres present a minimum attenuation of 60 dB/km and 120 dB/km. The loss of the 3-cell fibre shown in Figure 1(b) remains less than 100 dB/km over approximately 150 nm and we do not see surface modes. The GVD and dispersion slope of the 6.5 μm core fibre is large across the band gap and therefore the energy that would be required for soliton formation will be highly dependent on wavelength.

In contrast, both the 7-cell fibre and the 10 μm 3-cell fibre present slow varying dispersion at the centre of the bandgap. However, the 10 μm 3-cell fibre has a much higher dispersion (180 ps/nm/km) than the 7-cell fibre (20 ps/nm/km). The low dispersion slope of these fibres means that they could be used for re-compression of amplified pulses in all-fibre laser systems [7]. We anticipate that the larger nonlinearity of the 3-cell fibre will allow for the propagation of lower-energy solitons than previously [8], notwithstanding the higher dispersion.



(a) (b) (c)

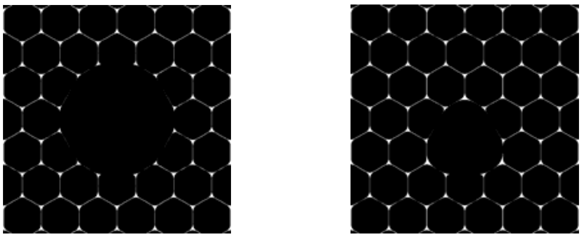
FIGURE 2. Measured attenuation and GVD of (a) 7-cell core, (b,c) 10μm and 6.5μm core 3-cell core fibres respectively. Please note that the graphs are to different scales.

NONLINEARITY OF 7 CELL AND 3 CELL CORE FIBRES

In this section the nonlinear properties of fibres with different core sizes are numerically studied. Firstly, we compare fibres with the same cladding structure but different core designs (7 and 3-cell cores). Then we vary the cladding structure (air-filling fraction and pitch Λ) of a seven-cell fibre. Note that if the air-filling fraction is reduced the size of the whole structure has to be scaled down in order to keep the bandgap at a fixed wavelength.

Nonlinearity of 3-cell and 7-cell core fibres

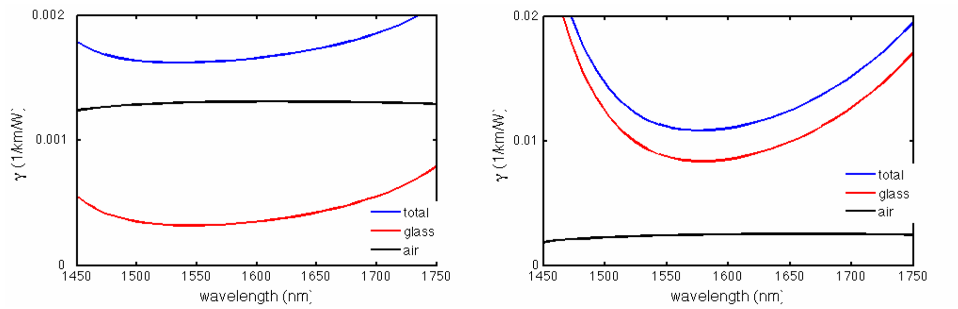
Cross sections of the 7-cell and 3-cell core air-guiding fibers are shown in Figure 3(a,b) respectively. The cladding is similar to that of the fibre in Figure 1(a); hexagonal holes with rounded corners, relative hole size $d/\Lambda = 0.98$, curvature at the corners $d_c = 0.41\Lambda$, and $\Lambda = 5$ μm. The 7-cell fibre has a core of ~ 15 μm while core size of the 3-cell fibre is ~ 10 μm.



(a) (b)

FIGURE 3. Cross-section of the modeled HC-PBGFs (a) 7-cell core, (b) 3-cell core.

The calculated nonlinear coefficient (γ) as a function of wavelength of the 7-cell and 3-cell fibres is shown in Figure 3(a,b). Across the bandgap, the nonlinear coefficient of the 7-cell fibre has lower dispersion than the the 3-cell fibre. The nonlinearity of the 3-cell fibre is ~6.5 to 12 times larger than that of the 7-cell. At the centre of the bandgap (1575 nm), the contribution from air to the total nonlinearity of the 7-cell design is 4 times larger than the glass contribution. However, in the 3-cell fibre the mode is a lot more extended into the cladding and the contribution from glass is ~ 4 times larger than from air.



(a) (b)

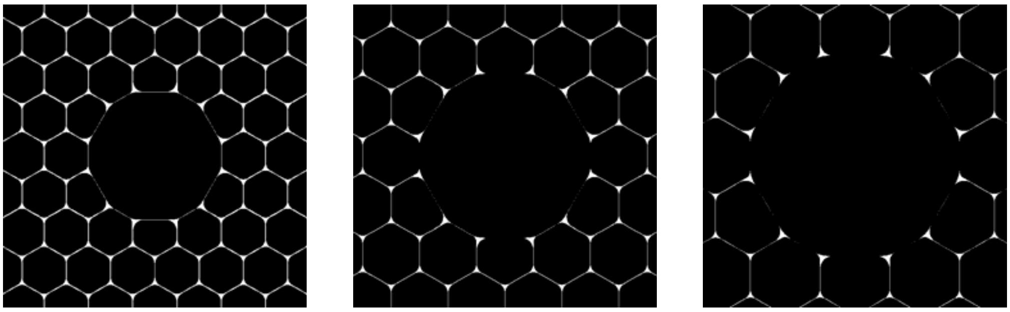
FIGURE 4. Calculated nonlinear coefficient as a function of wavelength for (a) 7-cell core, (b) 3-cell core fibres. Black line is the air contribution, red line glass, and blue is the total γ.

Nonlinearity of 7-cell Fibres with Different Cladding Designs

While fixing the high frequency edge of the bandgap, the air-filling fraction and Λ of a 7-cell fibre was varied. Cross sections of the analyzed fibres are shown in Figure 5 (box size 24 μm x 24 μm). Λ = 3.5 μm, 4.5 μm, and 5.5 μm for the fibres in Figure 5(a,b,c) respectively, while the core diameters are 10.5 μm, 13.5 μm and 16.5 μm respectively.

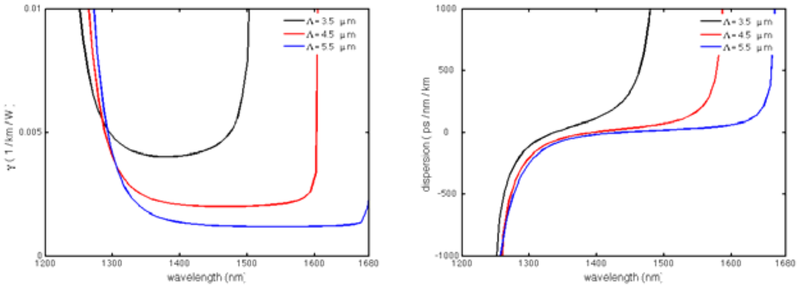
The nonlinear coefficient of the different fibres is plotted in Figure 6(a). As Λ (and air-filling fraction) increases, the transmission spectral width increases. The nonlinearity of the 3.5 μm fibre is only 3.4 times larger than the nonlinearity of the 5.5 µm pitch fibre. Although the difference in the core size between these two fibres is similar to the difference between the 3-cell and 7-cell core fibres analyzed in the previous section, the increase in nonlinearity achieved here is smaller than by changing the core from 7-cell to 3-cell. The nonlinearity of the 4.5 µm and the 5.5 µm pitch fibres are quite similar - flat at the centre of the bandgap and increasing sharply near the bandgap edges.

The GVD curves in Figure 6(b), show that the dispersion slope of the 3.5 µm pitch fibre is large across all the transmission band and both the 4.5 µm and the 5.5 µm pitch fibres have a region of flat dispersion at the centre of the bandgap.



(a) (b) (c)

FIGURE 5. Cross-section of the modeled HC-PBGFs, shown box 24 µm x 24 µm. (a) Λ = 3.5 µm, (b) Λ = 4.5 µm, and (c) Λ = 5.5 µm.



(a) (b)

FIGURE 6. Calculated (a) nonlinear coefficient and (b) GVD as a function of wavelength for 7-cell fibres with different cladding structures.

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