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All-silica, large mode area, single mode photonic bandgap fibre with Fabry–Perot resonant structures

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ABSTRACT

All-silica, photonic crystal fibres consisting of a low index, silica core surrounded by higher index inclusions embedded in a silica matrix to form a photonic bandgap cladding were numerically analysed. The aim of the investigations was to modify the guiding properties of the fibre by introducing resonant structural entities. These structural modifications are realised by altering the refractive index of certain high index inclusions in the photonic crystal cladding resulting in mode coupling between the core mode and the mode propagated in the modified index region. This results in an increased effective core area of the fundamental core mode and consequently decreased nonlinearity as well as modified effective index compared to the effective index of the unmodified structure and resonant dispersion profile that can be used for pulse compression or optical delay purposes.

1. Introduction

Normal optical fibres, consisting of a high refractive index core and low refractive index cladding, propagate light by means of total internal reflection. Photonic bandgap (PBG) fibres, however, consist of a core with a lower refractive index than the average cladding index and waveguidence only happens if the cladding is able to open up a bandgap in a plane perpendicular to the propagation. In this case, the core modes remain confined in the low-index region and can propagate along the fibre. The photonic bandgap effect can be achieved by periodic low and high index structural entities surrounding the core region [1].

PBG fibres with high and low index cladding patterns show the typic dispersion functions for PBG structures. This is true for one (dielectric mirrors) or more dimensional forms of the bandgap structures. The dispersion within the bandgap increases monotonically from the shorter to the longer wavelengths, resembling a third order function having steeper courses close to the edge of the bandgap and a positive dispersion slope in the entire wavelength range where the fibre has low loss, namely in the bandgap [2].

Recent ultra-short fibre laser and amplifier developments lack effective, monolithic dispersion management for higher orders and the common practice is to use chirped-mirrors to compress high power, ultra-short laser pulses [3]. The higher order dispersion contribution to the pulse evaluation from the optical components (optical fibres, isolators, couplers, splitters etc.) introduces a net third order dispersion (TOD) to the propagating pulse. This may also introduce some temporal distortions on the pulse if the pulse is short enough but TOD can be compensated by an optical element having negative dispersion slope. This requires dispersion modification of existing PBG fibres and broad resonances in the dispersion profile may result in negative dispersion slope at the long-wavelength edge of the resonance which can compensate the positive TOD contribution of other optical elements [4,5].

In telecommunication applications, specialty fibres may provide new possibilities in all-optical switching and ultra-fast wavelength division multiplexing (WDM) systems. This field requires fibres having resonance peaks in the dispersion function with relatively low losses in order to introduce some delay between the different channels. PBG fibres have different dispersion values at different frequencies but these differences are too small to achieve significant delay between channels using sufficient lengths of fibres. Dispersion tailored PBG fibres with narrow resonances and high peak values could be effectively used in time-gated filters [6], photonic time-stretched analog to digital converters [7] and in systems applying phase ripple correction [8].

The attempt to produce resonances in the bandgap and modify the dispersion for the fundamental optical mode in a waveguide is

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not a novel approach and was first demonstrated and calculated for Bragg fibres applying a dielectric confinement region around the core [4,9]. Negative dispersion slope was also achieved by modifying the hole size and shape of the first and second periods in a hollow-core PBG fibre with honey-comb cladding [10]. It turned out that the modification of the first period only in the same type of hollow-core fibre may yield resonant dispersion behaviour with more than 100 nm bandwidth [5]. We note however that the stored energy of the light in the resonant cladding structures cause mode field distortion which may lower the focusability of the output or the coupling efficiency to an other optical fibre [11]. Resonance structures in the cladding region of a PBG waveguide also can suppress higher order modes (HOM) in the air-core in a narrow wavelength range [12].

Increasing the core size is essential for high power pulse transmission and amplification in any kind of optical fibres to be appropriate for the recent demand of ultrashort and high power fibre lasers [13–17]. Increased core area can reduce the problems caused by the nonlinearity, mostly self-phase modulation (SPM) but in the same time it can lead to HOM propagation which lower the beam quality and it makes impossible such applications like reliable attosecond generation [18]. The usage of endlessly single mode photonic crystal fibre is reasonable to avoid HOM propagation [19]. Index guiding microstructured fibres have an embedded central core in a two-dimensional photonic crystal lattice with a hexagonal array of air holes. These type of fibres can be single mode for any wavelength and any core size [19]. In this case, the higher-order modes escapes between the holes with the fundamental mode confined in the core. The same single-mode operation can be achieved with photonic bandgap fibres with the same structure but replacing the air holes with high index inclusions [20]. The attempt to introduce resonant structures in the cladding in such microstructured and PBG fibre is presented by changing the hole size of the first period and the hole-to-hole spacing (pitch) between the first and second ring of high index inclusions [2]. These complicate structural modifications may be difficult to realise with the traditional stack and draw manufacturing process of these fibres.

In this paper, finite element calculations on such PCF structures are presented in which the refractive index of some certain inclusions are modified whilst the fibre geometry, uniform diameter and distance of the inclusions across the fibre, remains constant. These modified refractive index regions may introduce a wavelength dependent mode coupling with the fundamental core mode. This may result in resonant guiding properties of the fibre which can be utilised where special dispersion properties are required. We finally demonstrate by numerical analysis solving the nonlinear propagation equation for short pulses that the designed fibres can be applied effectively for pulse compression purposes.

2. Results

We solve the Helmholtz eigenvalue equation on the fibre cross-section using the Finite Element Method (FEM) [21] and a perfectly matched layer (PML) around the geometry to obtain the complex effective index (eigenvalue) which is used to calculate the dispersion and loss properties of the fibre. We use the obtained mode profile (eigenvector) to calculate the effective core area and the stored energy in the fibre structure. Fig. 1 shows a PCF structure of a SiO_2 glass fibre with the higher index inclusions arranged in a hexagonal lattice with large pitch values in order to obtain large mode field area. The high index inclusions in similar fibres are typically GeO_2 doped glass and we choose a refractive index 0.015 larger in absolute value than the low index silica at any calculated wavelength which is rheologically adequate. The silica refractive index is calculated from the Sellmeier equation [22] and the refractive index of the GeO_2 doped glass is adjusted to that value:

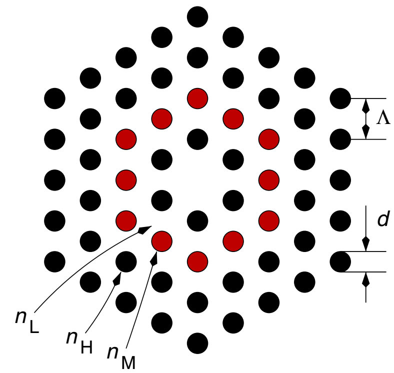

Fig. 1. All-silica PCF with low index silica matrix (n_L), high index inclusions (n_H) in the cladding and modified index inclusions (n_M) in the second period of the photonic crystal cladding. The pitch of the fibre is Λ while the diameter of the inclusions are uniform with a diameter of d.

$$n_H(\lambda) = n_L(\lambda) + \Delta n \tag{1}$$

where λ denotes the wavelength of the propagating light, n_H and n_L are referring to the high index regions and low index regions in the fibre geometry, respectively and Δn is the difference between the high and low refractive indices what we choose now as 0.015. The fibre cross-section in Fig. 1 differentiates the modified refractive indices of certain inclusions which are now the ones in the second period around the core. We will refer to the modified index period around the core by n_{M1} if the modified period is the first period of inclusions around the core, by n_{M2} if the modified period is the second period around the core and so on.

2.1. The introduction of the resonances

In the first calculation series, we present the dispersion and loss properties of the fibre if all inclusions are uniform and also in that case if we lower the refractive index of the second period of inclusions around the core using the parameter set given in Table 1. One can see that the second period of inclusions has just a 0.005 higher refractive index value than the low index silica matrix which can be easily prepared by the usual stack-and-draw technique using doped glass rods in the fibre preform with lower GeO_2 concentration in the second period around the core.

Fig. 2 shows the dispersion and the confinement loss of the propagating, fundamental core mode for three different n_{M2}. For $n_{M2} = n_L + 0.005$, there is a resonance in the dispersion profile and a negative dispersion slope between 1332 nm (1.332 μm) and 1452 nm (1.452 μm) which is a 120 nm wide bandwidth can be achieved that way that the first order dispersion is anomalous in the whole wavelength range. Decreasing n_{M2} to $n_L + 0.004$ results in narrowing and blue shifting the resonance. There is a greater confinement loss of the fibre compared to the unresonant fibre structure ($n_{M2} = n_H$) but it remains below 1 dB/m over the

Table 1
Parameter list of the fibre cross-section given in Fig. 1. Refractive index values are given at 1 μm.

Parameter	Value
d	2.9 μm
Λ	8.7 μm
n_L	1.4504
n_H	1.4654
n_{M2}	1.4554