Dispersion management in nonlinear photonic crystal fibres with nanostructured core

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The subwavelength structure of the core of a photonic crystal fibre can modify its dispersion characteristic and significantly shift the zero dispersion wavelength. The dispersion properties of photonic crystal fibres with core structures made of a 2D lattice of subwavelength air holes and various glass inclusions are studied. We show that a modification of the core structure can give flat dispersion over a range of over 300 nm and can shift the zero dispersion wavelength over 700 nm while the core diameter and photonic cladding remain unchanged. The developed photonic crystal fibre with nanorod core has successfully demonstrated supercontinuum generation in NIR.

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1 INTRODUCTION

Photonic crystal fibres (PCFs) are a very efficient medium for supercontinuum generation [1]. The manipulation of the photonic cladding parameters allows tailoring of the dispersion properties of the fibre. For silica-based photonic crystal fibre the zero dispersion wavelength (ZDW) can be shifted into the visible region and a range of pulsed sources can be efficiently used for broadband supercontinuum generation covering the entirety of the visible and near infrared spectrum.

Recently a lot of interest has focused on nonlinear PCFs made of tellurite and heavy metal oxide glasses, because these materials offer much higher nonlinear coefficients than silica glasses and more broadband transmission into the mid IR range [2]. However the dispersion properties of the fibres with simple photonic cladding prevent the use of efficient pump sources since the ZDW is placed in the IR region beyond 1.6 μm. A reduction of the core diameter allows a shift of the ZDW to shorter wavelengths, but simultaneously the attenuation of the fibre and coupling losses increase dramatically.

Recently the possibility of the manipulation of the fibre properties by structuring of the core has been developed for sensor applications [3, 4]. A multiply highly doped area in the core was used to enhance the nonlinearity of a photonic crystal fibre and permit the efficient broadening of the supercontinuum spectrum [5]. The concept of engineering of dispersion properties in PCFs with subwavelength single air holes in core was introduced and modeled by Saitoh et al. [6]. Tailoring zero dispersion and flat dispersion achievement was presented. Kibler et al. shown that introduction of subwavelength single air holes in core was introduced and modeled by Saitoh et al. [6], tailoring zero dispersion and flat dispersion achievement was presented. Wiederhecker at al [8], Ruan at al. [9] and Liu at al. [10]. In these cases a modification group velocity dispersion is also observed. The works [8, 9] focus on a possibility of field enhancement in the subwavelength air core, while Liu at al. shows that structuring a core of PCF may lead to a stable soliton self-frequency shift and subpetahertz sideband generation through four-wave mixing [10]. Recently the concept of a fibre with an array of microporous air-suspended core PCF based on chalcogenide glasses was introduced and modeled...
by Ung and Skorobogatiy [11]. The possibility of a red-shift of the ZDW to 10.5 μm was shown.

In this paper we propose to structure a core of the PCF with high index inclusions to tailor its dispersion properties and blue shift of zero dispersion wavelength. In this case the core of a standard PCF with air-hole cladding is structured with a single subwavelength rods.

2 Design of photonic crystal fibres with nanostructured core

We consider in the simulations various pairs of two thermally matched glasses (NC-21, SF6 and F2 air glass) to build subwavelength structures in the core. The structures with a high and low contrast are modelled. The modal and dispersion properties of the PCFs are calculated by means of a finite element method (FEM) using the COMSOL Multiphysics software [12]. We study the influence of core structure on the fibre dispersion in terms of the nano-sized rod diameter and their distribution. In addition, the simulation takes into account the material dispersion of the considered glasses through the Sellmeier coefficients [13].

To determine the character of the dispersion modification, we have performed indicative simulations. In the simulations we compare the dispersion properties of PCFs with air and high refractive index inclusions for a selected structure with the lattice constant \( \Lambda = 2.0 \text{ nm} \) and filling factor \( f = 0.95 \). We assume the presence of a subwavelength 2D regular hexagonal structure composed of a 7x7 array. The subwavelength structure has the lattice constant \( \Lambda_c = 300 \text{ nm} \) with inclusions of the diameter of \( d_c = 100 \text{ nm} \). As a background glass, the low index borosilicate glass NC21 synthesised in-house at ITME is used. A heavy metal oxide glass (SF6) and air are used as subwavelength inclusions in the core. Simulation results show that the structure of the core has a strong influence on the dispersion characteristics (Fig. 1).

It might be unexpected to see that the red shift of the ZDW is observed for both cases high and low inclusions with respect to a similar structure of PCF with a solid core. However, the origin of the red shift of the ZDW is different in both cases. For the air hole nanostructure, this behaviour is related to the lower effective refractive index of the core. Similar behaviour was previously reported in case of single air hole inclusion [6, 8]. Consequently for high index inclusions we would expect a blue shift of the ZDW. However this effect is compensated for by the material dispersion properties of the high index glass. Since the ZDW for bulky heavy metal nonlinear glasses is beyond 1.9 μm this effect is dominant and a red shift of the ZDW is observed.

Although a successful development of PCF with a single nanohole was previously reported [8]–[10], the development of PCFs with a regular lattice of subwavelength air holes in the core still remains a challenge for fiber technology [14]. Therefore an interesting alternative approach seems to be the use of subwavelength high index glass inclusions in the core. An additional advantage of this approach is an increase of the glass nonlinearity in the core which influences the efficiency of the nonlinear phenomena in the fibre. The introduction of a subwavelength structure results in a red shift of the ZDW (Fig. 2).

It is important to note that the effective mode area of the considered fundamental modes in the successive structures depends on the number of rings. Therefore structures with a single high index inclusion and with a standard solid core might have similar dispersion properties but very different effective mode areas.

In case of a single subwavelength inclusion of high index glass in the core, the fibre dispersion properties will vary with the diameter of the inclusion. A decrease of the inclusion diameter results in a blue shift of the ZDW for fundamental modes (Fig. 3). On the other hand, an increase of the inclusion causes decrease of effective mode area of the fundamental mode (Fig. 4).

It is important to note, that the excitation of the fundamental mode with a very small effective mode area is of low efficiency and therefore the second mode will play a dominant role in the energy transfer and will determine the dispersion properties of the fibre. The modal and dispersion properties of this second mode are very different from those of the fundamen-
3 Development and characterization of photonic crystal fibre with nanostructured core

Based on the performed simulations we have recently developed a PCF with the high index SF6 inclusion in the core. The fibre is made of silicate glass NC21 (55% SiO2, 1%Al2O3, 26% B2O3, 3% Li2O, 9.5% Na2O, 5.5% K2O, 0.8% As2O3) synthesized in-house with refractive index of \( n_D = 1.518 \). Nonlinear Kerr refractive index of NC21 glass is close to that of pure silica and has been measured as \( 1.1 \times 10^{-20} \text{ m}^2/W \) [13]. The fabricated fibre is composed of seven rings of holes ordered in a hexagonal lattice with filling factor of \( f = 0.91 \) and the lattice constant of \( \Lambda = 2.2 \mu \text{m} \) (Fig. 6). The core is created by replacement of the central capillary with tubes made of similar glass NC21 with a SF6 rod. The core has a diameter of 2.2 \( \mu \text{m} \) while the SF6 nanorod has a diameter of 450 nm.

The parameters of the developed PCF are slightly different those of the modelled one in previous chapter. Therefore modal and dispersion properties were simulated based on SEM photo taking into account all fabrication imperfections (Fig. 7). We have identified that ZDWs for fundamental mode located in the high index subwavelength inclusion are placed at 1763 and 1773 nm for orthogonal polarization components.
pumped in anomalous dispersion regime. However at the beginning self phase modulation is responsible for peak broadening since pump wavelength is near ZWD of the fiber at the normal dispersion side. With increased of wavelength a soliton can formed in proximity to the pump at anomalous dispersions wavelength. For low input power second peak is observed at longer wavelength with respect to pump wavelength. A red shift of this peak with increasing power can be observed until 990 nm when pulse energy is increased. This phenomena can be explained with soliton-self frequency shift (SSFS).

As the input power is further increased up to 2.6 nJ of energy pulse a red-shifted soliton brunch with intensity peak at 990 generates blue-shifted dispersion wave with maximum peak at 700 nm. In order to find out whether the dispersion wave are responsible for generation of spectra in short and long wavelengths range we have modelled phase matching conditions between hypothetic soliton and dispersion wave in the fiber according to equation [10]:

$$\delta \beta = \beta(\omega) - \beta(\omega_s) = \sum_{m=2}^{M} \frac{\beta_m(\omega - \omega_s)}{2!} - \frac{\gamma P}{2}$$  \hspace{1cm} (1)$$

where $\beta_m$ coefficients denotes the $m^{th}$ order derivative of $\beta(\omega)$, calculated at pump wavelength $\omega_s$, $\beta_m = \delta^m \beta / \delta \omega^m |_{\omega_s}$, $\gamma$ is the fiber nonlinear coefficient and $P$ is the soliton peak power. The calculated $\beta_m$ values of the expansion for the considered mode at $\lambda_0 = 807$ nm. Phase matching between 990 nm soliton peak and 696 nm peak for the developed fiber is shown in Fig. 10. The existence of the soliton shows the anomalous dispersion of excited modes and proves the efficient coupling into the second mode.

Further increases in the spectrum are limited by the low energy of the input pulse. On the other hand use of longer fiber doesn’t bring further improvement of the spectrum due to high attenuation of the fiber.

We have performed supercontinuum generation with a low power femtosecond oscillator (Fig. 8). As a pump we have used a Ti:Sapphire laser with a pulse width of 100 fs and pulse energy up to 2.6 nJ at 807 nm. The coupling efficiency between the laser beam and the measured fibre is 35%. Experimentally, supercontinuum generation in the range 665-1055 nm with flatness below 12 dB has been achieved in a 14 cm long section of PCF for 2.6 nJ input pulse energy. The generated spectrum for various pulse energies is shown in Fig. 9.

The obtained spectra shows typical behaviour of fiber respectively. Effective mode area is 0.38 $\mu m^2$. ZDWs for polarization components of second mode are 832 nm and 849 nm, respectively. Effective mode area for this mode is 3.77 $\mu m^2$. Nonlinear coefficient for the fiber at pump wavelength 807 nm is $\gamma = 23.1$ W$^{-1}$km$^{-1}$. However if we take into account a nanostructured character of the core we should use a modified nonlinear coefficient proposed by Afshar [15]. In this case nonlinear coefficient is higher $\gamma_V = 28.5$ W$^{-1}$km$^{-1}$.

The obtained spectra shows typical behaviour of fiber
[16]. We assumed in this case propagation of dominant second mode with Y polarization. Very similar results are obtained if the second mode with X polarization is considered. Based on the simulation results, we obtain a slightly narrower spectrum in the range 660-960 nm (Fig. 11). In general, the simulated spectra are in good agreement with the experimental results. The differences between the spectra are due to the contributions of higher order modes to the experimental spectra. Furthermore, the fundamental mode can provide an increased contribution due to the increasing effective mode area with wavelength (Fig. 4) and hence, energy transfer between the second and fundamental modes.

The simulations show spectral features with a maximum intensity at 670 nm due to a dispersive wave clearly related to the soliton peak near 950 nm. However, it should be noted that experimentally we obtained a peak that is identified as the one related to a dispersive wave at 695 nm. The differences can be related to errors in dispersion characteristics used in simulation calculated based on arbitrary thresholded SEM photo of the fiber.

4 Conclusions

The introduction of subwavelength holes in the core of PCFs allows the modification of the fibre dispersion characteristics. The introduction of high-index central subwavelength elements in the core may result in dramatic changes of general parameters of the fiber, where effective mode area of fundamental mode is reduced. In this case the second mode becomes dominant and anomalous dispersion over a long near IR range is obtained. A PCF made of NC21 silicate glass with air-glass cladding and core with subwavelength rod of SF6 glass was fabricated and the successful generation of a supercontinuum in the range 665–1055 nm with a flatness of 12 dB using low energy femtosecond pulses at 807 nm was observed.

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References


