

Reversed dispersion slope photonic bandgap fibers and femtosecond pulse propagation

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Abstract: Reversed dispersion slope PBG fibers are presented around one micron by the introduction of partial reflector layer around the core resulting in a strongly wavelength dependent nonlinear phase shift on the propagating fundamental mode.

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1. Introduction

Photonic bandgap (PBG) fibers [1] are attractive candidates of making good quality pulse compressions in fiber lasers [2] and amplifiers [3] at the ytterbium wavelengths. Two important features of PBG fibers make this available (i) the dispersion is usually anomalous around the center of the bandgap and (ii) the propagating mode is confined in a hollow core which can exhibit low nonlinearity even at elevated intensities.

PBG fibers however may cause temporal and spectral asymmetries or introduces satellite pulses using them in broadband dispersion control [4] mainly due to the third order dispersion contribution of the fiber which results in residual higher order spectral phase on the pulse responsible for asymmetries. Thus an ideal pulse compressor should have as well anomalous dispersion and low nonlinearity as negative dispersion slope which can be realized by structural modifications such as applying resonant layers in the cladding region [5,6].

We reported our theory to modify the dispersion profile of solid core (SC) and HC PBG fibers by introducing a two dimensional Gires-Tournois (GT) cavity around the core adopting the analogous from one dimensional PBG structures [6]. Calculations based on the finite element method (FEM) showed that the dispersion slope of PBG fibers can be changed with a properly adjusted first period which becomes the low reflecting mirror in a GT interferometer causing a frequency dependent higher order mode (HOM) field distribution resulting in a nonlinear group delay on the pulse. Now we aim to design an improved, realistic HC PBG cladding structure which is able to yield reversed dispersion slope (RDS) over a wide wavelength range (~100 nm) for the propagating fundamental mode not only HOMs. We demonstrate this possibility at SC Bragg fibers too where the small index difference between the alternating low and high index layers introduces some restrictions on fiber design to achieve the required dispersion profile. Femtosecond pulse propagation is also modeled to show that the designed fiber may be an essential tool to reach the sub-100 fs region with high power (>>100 mW) all-fiber devices.

2. Fiber design

The realization of GT cavity around the core can be represented by a readjusted first period. The design of this period can be realized depending on the cladding structure of the PBG fiber [6]. In the case of SC Bragg fibers the solution can be a doped layer around the core with a refractive index between the low and high index layers. It's thickness do not have to satisfy the quarter-wavelength (QW) condition resulting in a low reflectance. In the case of all-silica HC fibers this layer can be presented by a detuned first period changing the thickness of the first air layer whose reflectance can be further reduced by decreasing the thickness of the core wall (first high index layer) in the same time.

The high reflector part of the GT arrangement is the first properly designed PBG cladding where the high and low index layers satisfy the QW condition. In Fig. 1(a), a realistic standard 7-unit-cell hollow-core PBGF without core expand is shown. In order to modify the first period and its reflectance, the core radius is increased without affecting rest of the structure shown in Fig. 1(b). The core size is determined by the parameter R_c as shown in Fig. 1(c), and it is expressed as

$$R_c = (E+1)(1.5\Lambda - t/2) \quad (1)$$

where E stands for an expansion coefficient, Λ is the pitch (hole-to-hole spacing) and t is the core wall thickness.

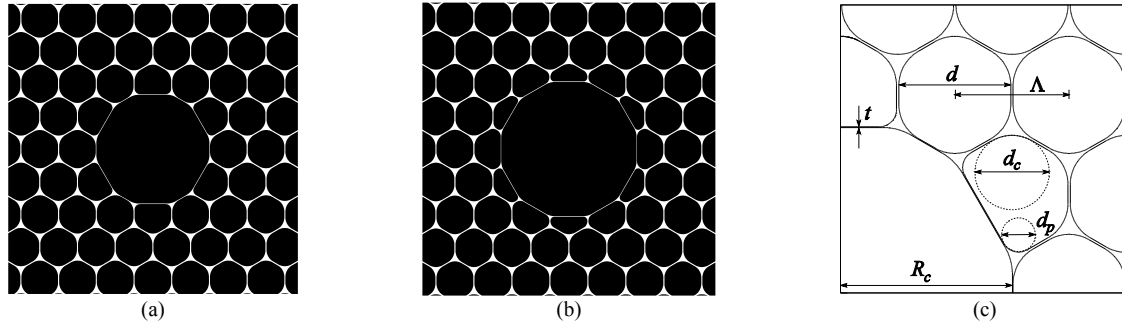


Fig. 1. (a) PBG fiber of honey-comb structure cladding, (b) the same structure with the applied core expansion, (c) fiber parameters.

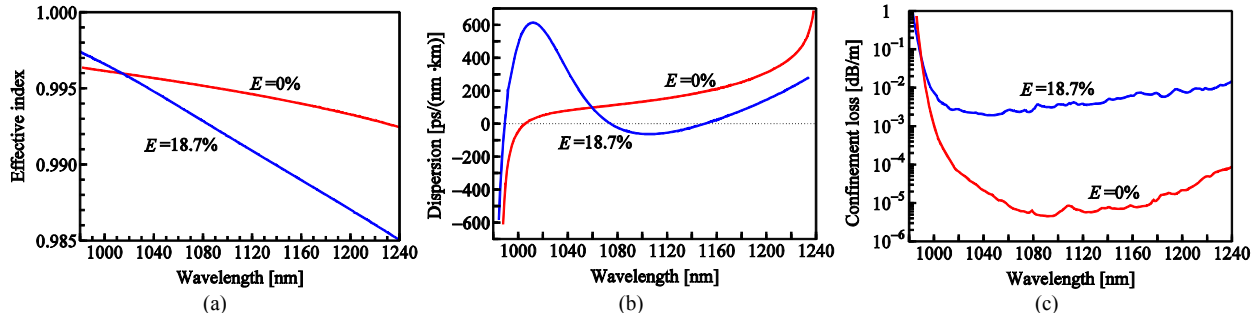


Fig. 2. Obtained FEM results of HC PBG fiber with and without core expansion: (a) effective index, (b) dispersion, (c) confinement loss.

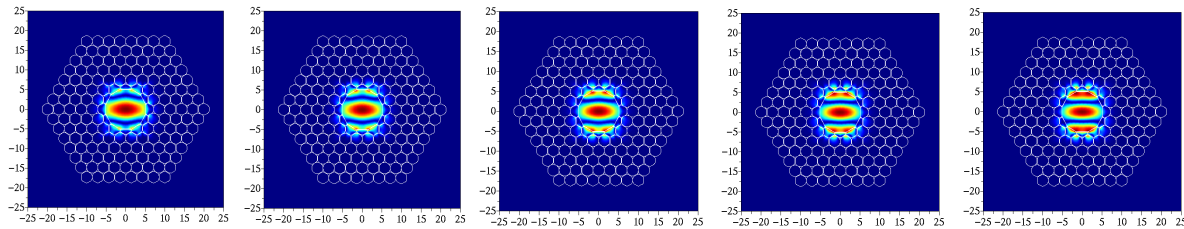


Fig. 3. Mode field distributions for wavelengths, from left to right, 1000, 1020, 1040, 1060 and 1080 nm of the LP_{01} mode which in fact shows an LP_{02} mode field distribution due to the GT resonances.

In order to increase the bandwidth of the inverted slope region in HC PBG fiber compared to that one obtained in Ref. [6] we observed that the increment of the d_c/Λ structural parameter may yield a wider RDS region. After the optimization of the structural parameters where we got $d/\Lambda=0.98$, $d_c/\Lambda=0.70$, $d_p/\Lambda=0.30$, $\Lambda=2.85 \mu\text{m}$, $t=0.3(\Lambda-d)$, the expansion coefficient is set as $E=0\%$ and 18.7% and using the fundamental air-core mode we obtained a 94 nm RDS around $1.06 \mu\text{m}$ (see Fig. 2). The expansion coefficient of 18.7% corresponds to the core size increment of 0.28Λ from the original core size shown in Fig. 1(a). Fig. 2(a), (b) and (c) are summaries of the effective indices, dispersion profiles and confinement loss curves of the designed HC PBG fiber with different core expansions, respectively. Although we plotted the fundamental core modes in Fig. 3, the mode field distribution is much more closer to an LP_{02} field distribution due to resonance coupling between the air-core mode and the low-index GT layer. For shorter wavelengths where resonant coupling does not occur fundamental mode is similar to an LP_{01} mode distribution.

SC Bragg PBG fibers with RDS or flat dispersion profiles can also be an important element of future all-fiber devices. Since these fibers has a solid core the nonlinearity is elevated compared to HC fibers and they could be well suited for applications where parametric processes are important.

In order to obtain a bandgap around $1.06 \mu\text{m}$ using fused silica as core and low index materials and doped silica with GeO_2 as high index one the obtained layer thicknesses after structural optimization were $6.2 \mu\text{m}$ and $0.99 \mu\text{m}$ for the low and high index materials, respectively. The refractive index of the doped and fused silica layers are 1.4997 and 1.4497 at $1.06 \mu\text{m}$. The introduced GT layer around the core is 1.21 times thicker than that of the low index layer having a refractive index of 1.4642 at $1.06 \mu\text{m}$. The thickness of low index annular layers had to be changed after the introduction of GT layer. The effective index changes as a function of the wavelength so strongly due to the resonance coupling with GT cavity that the mode may become leaky before obtaining an RDS. Therefore the modified structure has a low index layer thickness of $5 \mu\text{m}$. Calculation results are summarized in Fig. 4.

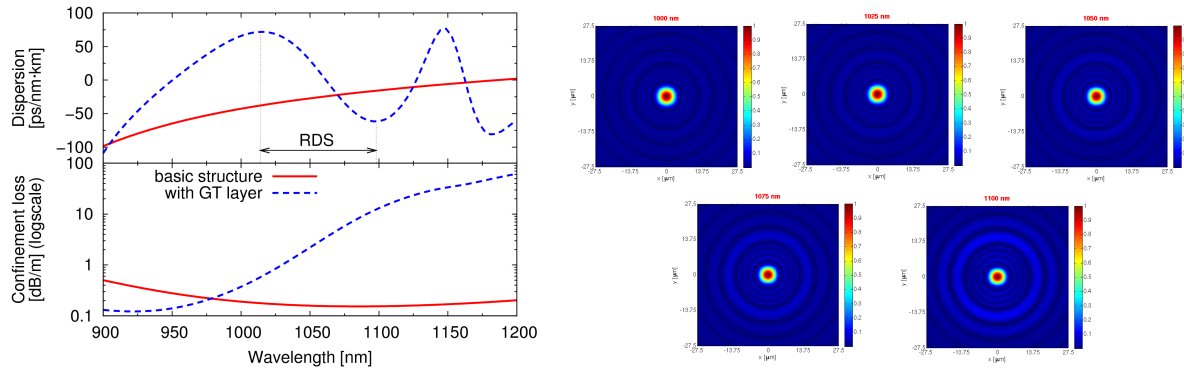


Fig. 4. Obtained dispersion and loss curves for SC Bragg fiber (left) and calculated mode field distributions with GT structure (right).

The obtained 84 nm RDS range from 1014 nm to 1098 nm can be extended close to 100 nm RDS range or even above by further optimization of the structure which process is under preparation.

3. Propagation analysis

We used the generalized nonlinear Schrödinger (NLS) equation to analyze the propagation of ultrashort and high-intensity pulses in HC PBG fibers. The nonlinear refractive index is chosen to be 100 times smaller than the nonlinear index of standard single mode fibers ($2.6 \cdot 10^{-22} \text{ m}^2/\text{W}$) and the dispersion properties of the HC fiber is approximated by Taylor-series up to the fifth order

$$\beta(\omega) = \beta_2(\omega - \omega_0)^2/2 + \beta_3(\omega - \omega_0)^3/6 + \beta_4(\omega - \omega_0)^4/24 + \beta_5(\omega - \omega_0)^5/120 \quad (2)$$

where $\beta_2 = -7.748 \cdot 10^{-2} \text{ ps}^2/\text{m}$, $\beta_3 = 3.64 \cdot 10^{-4} \text{ ps}^3/\text{m}$, $\beta_4 = 9.81 \cdot 10^{-6} \text{ ps}^4/\text{m}$ and $\beta_5 = 2.95 \cdot 10^{-7} \text{ ps}^5/\text{m}$ for HC-1060 fiber at 1.06 μm and $\beta_2 = -5.8468 \cdot 10^{-2} \text{ ps}^2/\text{m}$, $\beta_3 = -3.09 \cdot 10^{-3} \text{ ps}^3/\text{m}$, $\beta_4 = -4.66 \cdot 10^{-5} \text{ ps}^4/\text{m}$ and $\beta_5 = 6.85 \cdot 10^{-7} \text{ ps}^5/\text{m}$ for the RDS fiber with a dispersion curve plotted in Fig. 2(b) ($E=18.7\%$). We assume pulses with 40 MHz repetition rate and 500 mW average power corresponding to pulse energy of 12.5 nJ. We also assume that pulses have a bandwidth corresponds to 100 fs transform limited Gaussian pulse ($\sim 16.2 \text{ nm}$) and the pulse holds about 0.5 ps^2 linear phase modulation obtained from a gain medium or other optical components. The results with HC-1060 and also its combination with RDS fiber for different center wavelengths of the pulses are plotted in Fig. 5. It can be seen when compression ratio reaches about 7 fold compression quality factor (QF) decreases drastically and at maximum compression level only 40-60% of total pulse energy locates in the main peak. In the case of combined HC-1060 and RDS fibers we managed to obtain 110 fs pulses with 98.9% QF using 100 mW average power in this case (Fig.5(c)).

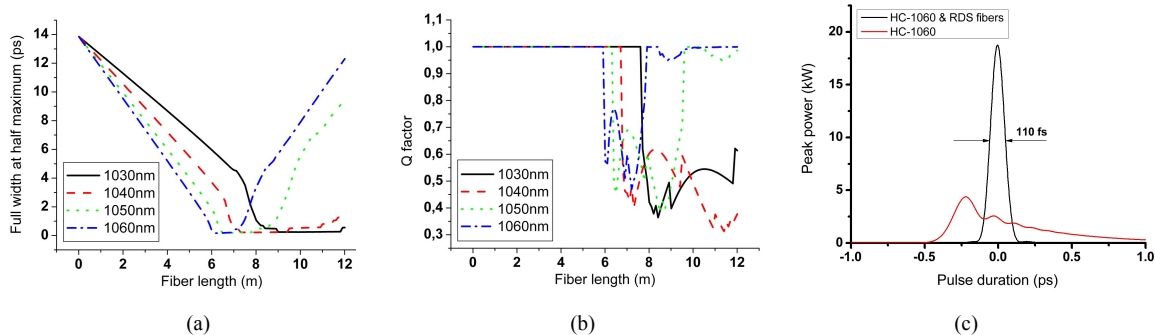


Fig. 5. (a) FWHM and (b) QF evaluation of pulses with different center frequencies in HC-1060 fiber. (c) Pulse shapes at maximal compression levels with 100 mW power in both HC-1060 fiber and HC-1060 combined with RDS fiber having their lengths of 5.92 m and 0.7 m, respectively.

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