

# Higher-Order Mode Photonic Bandgap Fibers with Reversed Dispersion Slope

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**Abstract:** Numerical simulations by the vector finite element method show that the dispersion slope of all-silica hollow-core Bragg photonic bandgap fibers can be adjusted by structural modification of a standard quarterwave cylindrical stack design.

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## 1. Introduction

Hollow-core (HC) optical fibers play an important role in high damage threshold cw or high intensity pulsed laser applications, since most of the optical power is guided in the air core. In contrast to standard single-mode fibers, wave guiding is based on the interference phenomenon of light, which can be realized in different forms, such as HC Bragg fibers [1], or HC photonic bandgap (PBG) fibers [2, 3]. In the former, the cladding is formed of concentric cylindrical dielectric layers with alternating high and low refractive indices, while in the latter the cladding consists of periodic air holes symmetrically arranged in a high index dielectric material. Recently, combining these two structures in sense of constituting materials (silica, air) and geometric layout (cylindrical layers), all-silica HC Bragg PBG fibers have been constructed: around an air core, a cladding is formed by concentric cylindrical silica layers separated by nanoscale support bridges [4]. We refer to them as HC Bragg PBG fibers in the followings. Typically, HC PBG fibers exhibit anomalous dispersion over most of their bandwidth. Unfortunately, their dispersion changes rapidly as the function of wavelength and have a limited bandwidth which hinders their application for distortion-free delivery [5] or dispersion compensation of broadband femtosecond laser pulses [6]. The problem of limited bandwidth of HC PBG fibers seems to be solved by the introduction of ultra-large bandwidth hollow-core all-silica Bragg PBG fibers with nano-supports [4]. So far, these fibers have not been commercialized and their dispersion properties have not been discussed in the literature yet.

In this paper, we utilize the analogy between 1D and 2D photonic bandgap structures, i.e., dielectric mirrors at grazing incidence and HC Bragg PBG fibers, for tailoring dispersion slope of these fibers. We use the vector finite element method (V-FEM) with perfectly matched layer (PML) for analyzing the dispersion and loss properties of quarterwave HC Bragg PBG fibers and we propose structural modifications of the quarterwave design paving the way to ultra-broadband dispersion control of high energy pulses.

## 2. Dispersion of quarterwave, ultra-large bandwidth, hollow-core Bragg PBG fibers

Dispersive and loss properties of quarterwave, ultra-large bandwidth HC all-silica Bragg PBG fibers were investigated as a function of core diameter, in the range of  $6 - 10\mu\text{m}$ . The structure consists of three pairs of alternating fused silica ( $H$ ) - air spacer ( $L$ ) layers. The effect of support bridges were not taken into account in our calculations. In practice, they increase the effective indices of the air layers by a value of 0.01-0.02 and are responsible for the appearance of leaking modes leading to high loss peaks in the spectrum with narrow bandgaps [7]. Our proposed method for reversing the dispersion slope of higher-order mode (HOM) PBG fibers is independent of this effect, that is why we use "ideal" air spacer layers ( $n_L = 1.0$ ) in our calculations.

Changing the core size affects both the bandwidth and dispersion of a Bragg fiber, since this parameter changes the effective "angle of incidence" of the fundamental mode. We found that a higher core radius results in a broader photonic bandgap, a lower confinement loss and a lower dispersion slope, which can be explained by the increasing effective angle of incidence in case of an increasing core radius. Compared to standard HC PBG structures, these HC

Bragg PBG fibers exhibit a considerably increased spectral bandwidth and lower dispersion slope, that could be well suited for broadband delivery and second order dispersion (group delay dispersion, *GDD*) control of femtosecond pulses. However, such designs do not allow cubic phase (third order dispersion, *TOD*) control, which becomes very important in applications aiming for sub-50 fs performance.

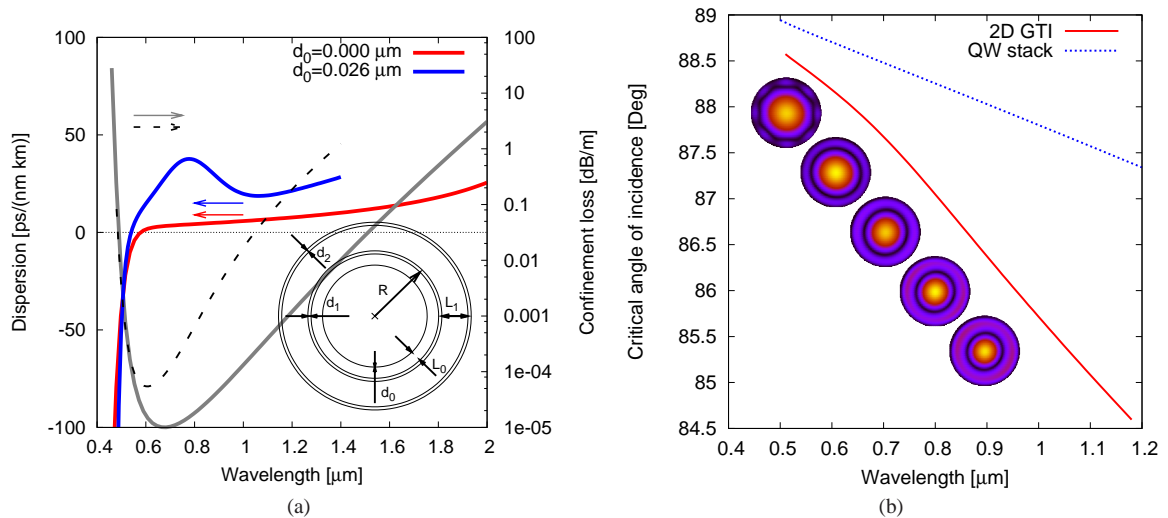


Fig. 1. (a) Computed dispersion and loss vs. wavelength of HC Bragg PBG structures with ( $d_o = 0.026\mu\text{m}$ ) and without ( $d_o = 0\mu\text{m}$ ) additional partial reflector layers,  $L_o = 1.08\mu\text{m}$ ,  $d_1 = d_2 = d_3 = 0.24\mu\text{m}$  thick fused silica cladding layers and  $L_1 = L_2 = L_3 = 4.78\mu\text{m}$  thick air spacer layers. (b) Computed critical angle of incidence vs. wavelength functions corresponding to quarterwave (QW) HC Bragg PBG structures with and without a GTI layer. Mode field distributions in the core of the HC Bragg PBG fiber with GTI layer are displayed for wavelengths of 500, 600, 700, 800 and 900 nm.

### 3. Tailoring dispersion slope of HC Bragg PBG fibers

Regarding spectral reflectance and confinement loss, the analogy between 1D PBG and 2D HC PBG structures has been established [7]. It was shown that under the asymptotic limit, the Bragg fiber cladding layers can be well approximated by a planar Bragg stack with the same physical parameters. During previous studies [8], it was found that the dispersion of 1D PBG structures, such as high reflectivity dielectric laser mirrors, originates from two physical effects: 1. the frequency dependent penetration depth of the electromagnetic field upon reflection, and 2. resonances in the layer structures. The former effect causes the positive *TOD* of quarterwave mirrors, and this physical effect was utilized for the development of chirped mirrors for dispersion control and feedback in ultrabroadband femtosecond pulse laser systems. The latter effect, i.e., resonances were applied for development of optical thin film, single- or multi-cavity Gires-Tournois interferometers (GTI), which can exhibit anomalous or normal dispersion over a limited bandwidth. Additionally, single cavity GTI-s can be utilized for cubic phase control; in contrast to quarterwave stacks, they can provide negative *TOD* over most of their reflection band (photonic bandgap).

Ultrabroadband HC Bragg PCF-s exhibit positive *TOD* over most of their bandwidth for the same physical reason as quarterwave stack dielectric mirrors. One would expect that chirping the HC Bragg PBG structure should have an effect on the bandwidth and dispersion slope of the design. Based on our computer simulations, we can say that chirping the Bragg structure does not result in considerable change of the dispersion profile, since in HC Bragg PBG fibers, the light is guided at grazing incidence. This results in a very high effective refractive index difference between the concentric fused silica and air layers around the air core (i.e., very high reflectivity at the fused silica/ air interfaces), which provides low attenuation even in case of a few fused silica cladding layers. Unfortunately, this high "coupling" does not allow tailoring the penetration depth according to the desired dispersion function, hence it seems to be impossible to realize a nearly constant dispersion over a broad frequency range in this way.

Considering these facts, we expect that the dispersion slope of HC Bragg PBG-s can be modified only by adding some additional partial reflector layer(s) to the previously discussed quarterwave design, resulting in a 2D *Gires-Tournois interferometer* Bragg structure. Here we propose two possible realizations, but other ideas might also work: 1. partial (ultra-thin) reflector layer is introduced into the core with some spacing from the first silica ring, 2. an additional low index core layer is placed next to the first silica ring providing some partial reflection on the air core / additional layer interface.

From the theoretical point of view, these two structures are equivalent and have the same physical effect on the dispersion function: they provide the spacer layer and the partial reflector of the 2D Bragg GTI structure. Because of realization concerns, we used the former one in our simulations. The additional layer (see Fig. 1 (a), inset drawing) is a  $d_0 = 0.026\mu\text{m}$  thick silica layer, and its distance from the original core boundary is  $L_0 = 1.08\mu\text{m}$ .

In Fig. 1 (a), we show how the dispersion slope can be modified by applying this additional partial reflector layer in the core. (For comparison, see  $d_0 = 0\mu\text{m}$  as the quarterwave stack design.) The dispersion behavior is very similar to 1D thin-film GTI-s: by increasing the value of  $L_0$ , the reversed dispersion slope can be shifted to longer wavelengths. This design provides anomalous dispersion and reversed dispersion slope over a  $\sim 200\text{ nm}$  bandwidth around  $1\mu\text{m}$ . The core size was set to  $10\mu\text{m}$  in both cases. In the case of thicker GTI layer, the bandgap becomes slightly narrower since the effective core size for propagating mode becomes smaller.

In Fig. 1 (b), we plotted the computed mode field distributions and the critical angle of incidence as the function of wavelength. Analyzing the mode field distributions we can say that the reversed dispersion slope originates from the GTI effect in case of this specific 2D GTI Bragg design: the longer the wavelength, the higher the energy stored in the GTI layer having a maximum value at around  $1\mu\text{m}$ . Like in the case of 1D GTI structures, this resonance results in a considerable negative  $TOD$  at  $1\mu\text{m}$  reversing the dispersion slope of the HC Bragg PBG design. It is to be noted that the modes contributing to the reversed dispersion slope are higher order modes.

For comparative purposes, in Fig. 1 (b) we plotted the computed critical angle of incidence vs. wavelength functions corresponding to the quarterwave stack design (see Fig. 1 (a),  $d_o = 0\mu\text{m}$ ) and the 2D GTI Bragg fiber (Fig. 1 (a)  $d_o = 0.026\mu\text{m}$ ). In case of the quarterwave stack Bragg fiber, the angle of incidence is a linear function of wavelength, while in case of the 2D GTI Bragg fiber, this function is nonlinear and the slope is considerably higher. We optimized our Bragg fiber design for an angle of incidence of  $87^\circ$ . The reason was that this value corresponds to computed angle of incidence at around  $1\mu\text{m}$  (our desired central wavelength of the bandgap), obtained from our V-FEM calculations. This information is necessary to obtain an optimum design meeting the requirement for quarterwave condition providing the highest bandwidth and minimum dispersion slope of the HC Bragg fiber. Furthermore, using this information one can use simple 1D simulations corresponding to attenuation and dispersion properties of 2D HC Bragg PBG fibers.

In this paper, we reported on our simulations on dispersive properties of different HC Bragg PBG fiber designs using the V-FEM. We have shown that properly designed quarterwave HC Bragg PBG fibers exhibit low attenuation loss, anomalous dispersion and normal dispersion slope over one octave or more. By slight modification of the design, we reversed the dispersion slope, i.e. the cubic dispersion of the Bragg fiber design, which design is a 2D equivalent of the 1D thin film Gires-Tournois interferometers, hence we referred to them as 2D HC GTI Bragg fibers. Combining quarterwave HC Bragg PBG fibers and 2D HC GTI Bragg fibers of proper lengths paves the way for ultrabroadband delivery and dispersion control of high intensity femtosecond laser pulses using fiber optic technology.

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