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# A highly nonlinear photonic quasi-crystal fiber with low confinement loss and flattened dispersion

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ABSTRACT

We proposed a novel photonic quasi-crystal fiber with near-zero flattened dispersion, highly nonlinear coefficient, and low confinement loss by using the dual concentric core structure. By optimizing the structure parameter, the proposed photonic quasi-crystal fiber can achieve a nonlinear coefficient larger than 33 $W^{-1}$ $km^{-1}$ and near-zero flatten dispersion of 0 ± 3.4 ps/nm/km with a near-zero dispersion slope of $8.5 \times 10^{-3}$ ps/$nm^2$/km at the wavelength of 1550 nm. Near-zero flattened dispersion and low confinement loss in the ultralow order of $10^{-7}$ dB/m are simultaneously obtained in the wavelength range from 1373 to 1627 nm. Furthermore, two zero dispersion wavelengths can be achieved in a wide wavelength ranger from 1373 to 1725 nm. From the point of view of practical fabrication, the influence of deviation of each air hole diameter within 3% of imperfections on dispersion, nonlinearity, and is discussed to verify the robustness of our design.



## 1. Introduction

Highly nonlinear (HNL) fibers are suitable for a variety of applications including wavelength conversion, optical parametric amplification, and super-continuum generation and so on [1]. Furthermore, HNL fibers with not only high nonlinearity but also low dispersion and dispersion slope are of great importance in their application [2–3]. Silica-based HNL fibers are well compatible with the conventional single mode fibers and therefore have great advantage in practical applications. Okuno et al. fabricated a highly nonlinear dispersion-flattened silica-based fibers with dispersion slope of 0.0002 ps/$nm^2$/km [4]. However, conventional HNL fibers have the limit of nonlinear coefficient to confine their application. Recently, HNL fibers based on photonic crystal fibers (PCFs) have been intensively studied to achieve better properties than conventional silica-based HNL fibers. Lots of PCFs with HNL and ultra-flattened dispersion characteristics have been reported to date. Razzak et al. proposed a HNL PCF with a nonlinear coefficient of 36.5 $W^{-1}$ $km^{-1}$ and a confinement loss of approximately $10^{-2}$ dB/km at 1550 nm [5]. An eight-ring PCF was reported with a nonlinear coefficient larger than 33 $W^{-1}$ $km^{-1}$ and a ultra-flat dispersion with a value between −1.380 and 0.986 ps/nm/km and a low-order confinement loss of $10^{-4}$ dB/km in the wavelength range from 1400 to 1625 nm [6]. HNL PCFs with identical air holes have also been reported [7,8], which have small nonlinear coefficient of 19 $W^{-1}$ $km^{-1}$ [7] or relatively large dispersion slope of −0.25 ps/$nm^2$/km [8]. But it is difficult to obtain highly nonlinear coefficient and flattened dispersion simultaneously due to the use of identical air holes in this structure. Although PCFs reported show significant improvements of the nonlinear and flattened dispersion characteristics [9–12], most of those PCFs have many designed parameters and the wavelength range need to be further expanded.

As a potential HNL fiber, photonic quasi-crystal fibers (PQFs) proposed by Soan Kim in 2007 have attracted much more attention in recent years due to their unique properties [13]. PQFs are novel micro-structured fiber with a quasi-periodic structure, in which there is a long-range order but no periodicity. Compared with PCFs, PQFs have some distinct properties such as ultra-flattened dispersion [13], larger cutoff ratio for endlessly single mode operation [14], two photonic band gaps with low loss guidance [15], and a very large dispersion, and large mode area characteristics [16]. A sixfold symmetric PQF exhibits almost zero ultra-flattened chromatic dispersion, 0 ± 0.05 ps/km/nm, in the wavelength range from 1490 to 1680 nm [13]. Up to now, most of the researches about PQF are mainly concerned the properties of dispersion and the properties of HNL about PQF have not been studied.

We proposed a novel photonic quasi-crystal fiber with dual concentric core structure in this paper. After the precise adjustments of the structure of PQF using different combinations of parameters, the optimum structure parameters can be obtained

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for the proposed structure which has near-zero flattened chromatic dispersion, highly nonlinear coefficient, and dual zero dispersion wavelengths (ZDWs) within optical communication window. To the best of our knowledge it is the first time to report the HNL PQF with flattened dispersion in optical communication window. The designed HNL PQF has a modest number of parameters, and only one air hole pitch, but it can yield relatively optimal properties. The robustness of our design is also taken into consideration. Our structure and optical properties predictions are expected to provide valuable characterization of properties variation with composition for these technologically significant materials while contribute basic data to aid in relative experiments.

## 2. Design methodologies

A novel dual concentric core silica-based PQF is proposed and its schematic cross section with a twelve-fold symmetry is shown in Fig. 1, which is composed of a pure silica background. From the point of view of practical fabrication, two sizes of air holes are adopted in the PQF proposed. The small size of air holes is arranged in the first and fourth rings to form the dual concentric core structure that can adjust dispersion property and thus flatten the dispersion and dispersion slope as well. Results of PCFs have shown that the value of the dispersion parameter can be significantly changed by reducing the air-hole diameter in the first ring, or decreasing by using smaller air holes in the second or in the third ring [10], that is to change the zero-dispersion wavelength [17] or to engineer the dispersion curve to be ultra-flattened [18].The diameter of small hole and big hole are denoted by d1 and d2, respectively. The air hole pitch is labeled $\Lambda$ as the distance between the centers of neighboring air holes.

To investigate the properties of PQF, the finite element method with scattering boundary condition is utilized. Benefiting from the geometrical symmetry, only a quarter of the PQF cross-section is needed to be computed. As shown in Fig. 2, the horizontal and vertical boundaries of the calculation area are assigned with Perfect Electric Conductor (PEC) and Perfect Magnetic Conductor (PMC) artificial boundary conditions, separately. A scattering boundary condition (SBC) is used to match the outmost layer.

Nonlinear coefficient is an important parameter for high nonlinear fiber and defined by [19]:

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}} \tag{1}$$

where $n_2 = 2.6 \times 10\text{–}20\ m^2/W$ is the nonlinear refractive index of pure silica material and represent the degree of nonlinear effects, $\lambda$ is the wavelength in vacuum.

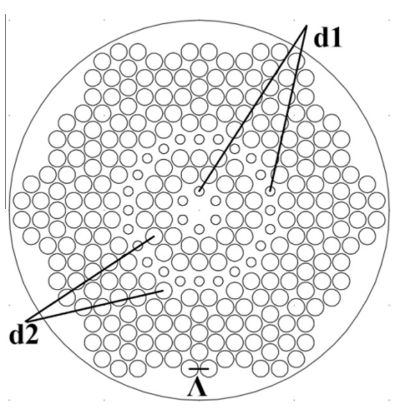


**Fig. 1.** Cross section of the proposed HNL PQF.

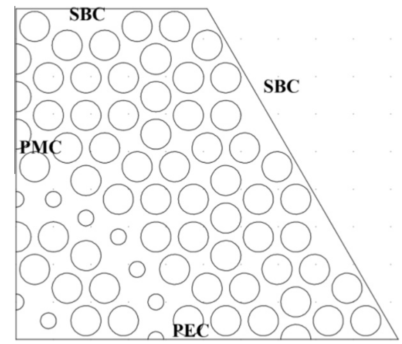


**Fig. 2.** Boundary conditions for computation.

The mode field area of the photonic quasi-crystal fiber can be expressed as [20]

$$A_{\text{eff}} = \frac{\left(\int\int_s |E|^2 dxdy\right)^2}{\int\int_s |E|^4 dxdy} \tag{2}$$

where $E$ is the electric field amplitude and s is the cross section of fiber.

The chromatic dispersion can be directly calculated from the effective index $n_{\text{eff}}$ of the fundamental mode [19]

$$D = -\frac{\lambda}{c}\frac{d^2 n_{\text{eff}}}{d\lambda^2} \tag{3}$$

where, $n_{\text{eff}}$ is the effective index and c is the velocity of light in vacuum.

Confinement loss reflects the light confinement ability within the core region and can be calculated as follows [20,21]:

$$Loss = -8.686\kappa_0 Im[n_{\text{eff}}] \tag{4}$$

where $Im[n_{\text{eff}}]$ is the imaginary part of the refractive index and $\kappa_0 = 2\pi/\lambda$ is the wavenumber in free space.

## 3. Optimizing design of the proposed HNL PQF

Dispersion and nonlinearity coefficient of PQF can be controlled by adjusting fiber geometry parameters, such as air hole diameter and holes pitch. There are three degrees of freedom (d1, d2, and $\Lambda$) in the design procedure. The dispersion and nonlinearity properties with those different structural parameters have been investigated and presented below. The original parameters are set as the following: holes pitch $\Lambda$ = 1 μm, the diameter of the small air holes in the first and fourth rings d1/$\Lambda$ = 0.4, the diameter of the big air holes d2/$\Lambda$ = 0.82.

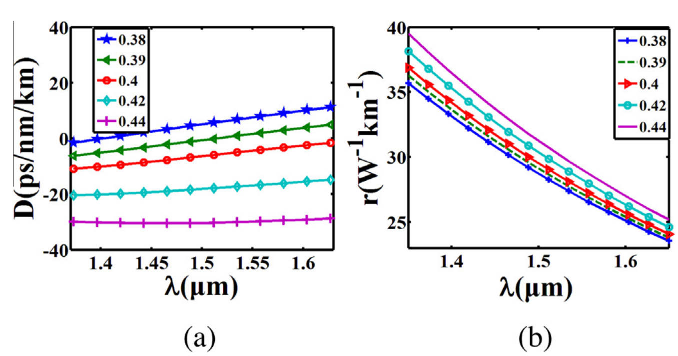


**Fig. 3.** Dispersion (a) and nonlinearity (b) of PQF with different d1/$\Lambda$, d2/$\Lambda$ = 0.82, and $\Lambda$ = 1 μm.