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Photonic Crystal Fibers with Optimized Dispersion for Telecommunication Systems

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1. Introduction

The use of Photonic Crystal Fibers (PCF) is understood within their unique chromatic dispersion characteristics and nonlinear behavior, which is suitable for dispersion compensation or transmission of information without pulse spreading, leading to an intersymbol interference. Pulse spreading being the result of chromatic dispersion in optical fibers is considered as one of the critical issues in the design of optical fibers. Since the dispersion can result in worse system performance, it is necessary to prevent its occurrence or to compensate it.
A systematic study of dispersion properties in PCFs is presented. The investigation includes a description of fiber chromatic dispersion dependence on structural and material parameters. Potential zero or anomalous dispersion in doped PCFs is achieved. An overview of current innovations on the studied problem is presented.
Moreover, the new PCF with nearly zero ultra-flattened chromatic dispersion is introduced. It is shown from the numerical results that the dispersion of –0.025 ps/nm/km is available from the wavelength of 1200 nm to 1700 nm.

2. Photonic crystal fibers

PCFs, also known as microstructured or holey fibers, are investigated in view of their unique properties of light guidance. Unlike conventional step-index fibers, PCFs guide light through confining field within microstructure periodic air holes. PCFs are characterized by the periodicity of refractive index, implemented as an array of air holes around the core. The guidance mechanism in some aspects resembles the operation of semiconductor materials. In other words, the photons in PCFs have a function, which is similar to the operating principle of electrons in semiconductors.

2.1 Types of photonic crystal fibers

PCFs are classified in two categories: solid core high-index guiding (or simply an index guiding) fibers and hollow core low-index guiding fibers. The Index Guiding Photonic Crystal Fiber (IGPCF) guides light in a solid core by Modified Total Internal Reflection (M-TIR). This principle is similar to the guidance in conventional optical fibers. The other

category of PCFs, Hollow Core Photonic Crystal Fiber (HCPCF) guides light by the Photonic Band Gap (PBG) effect. Light is confined in the low-index core, since the distribution of energy levels in the structure makes the propagation in the cladding region impossible.
The M-TIR principle of light guidance relies on a high-index core region, typically pure silica, surrounded by a lower effective index material, provided by air holes in the cladding.

2.2 New properties achievable in photonic crystal fibers

The effective index of such a fiber can be approximated by a standard step-index fiber, with a high-index core and a low-index cladding. However, the refractive index of a microstructured cladding in PCFs exhibits strong wavelength dependence very different from pure silica, which allows PCFs to be designed with a new set of features unattainable within the classical approach. For example, endlessly single mode PCF can be designed through the strong wavelength dependence of the effective index (reducing thus the value of normalized frequency, a parameter important for modal regimes). This is fundamentally different from the conventional fibers where, at huge core diameter to wavelength ratios, a multi-mode operation is unavoidable at shorter wavelengths, because the cladding index is constant and normalized frequency arises with wavelength, once exceeding the value critical for single-mode operation. In addition, the presence of air holes in the cladding can change the spectral characteristics of microstructured fibers.
Among PCFs with modified spectral properties, zero dispersion or anomalous dispersion fibers are very promising for group velocity dispersion compensation. The latest designs show optimal dispersion for broadband applications, in contrast to the commercially available compensating fibers, which can usually operate at a specific wavelength.

3. Photonic crystal fibers for dispersion compensation or zero-dispersion transmission

Chromatic dispersion directly affects the pulse width and the phase-matching conditions important for most telecommunications applications. Chromatic dispersion in lightwave systems is related to the variation in group velocity of optical signals in a fiber. The adjective "chromatic" emphasizes its wavelength-dependent nature. Chromatic dispersion limits the maximum distance, to which a signal can be transmitted without the necessity of regeneration of its shape, timing, and amplitude. The pulse spreading must be compensated or avoided, for example, by specific fiber design.
As far as basic terminology is concerned, when the chromatic dispersion coefficient is less than zero, the dispersion regime is said to be anomalous, and shorter wavelengths propagate faster than longer wavelengths. The pulse is said to be negatively chirped. In the opposite case of dispersion coefficient being greater than zero, the dispersion regime is said to be normal. Long waves are guided faster than the short ones.

3.1 Engineered chromatic dispersion in photonic crystal fibers

The mechanism of light dispersion depends on various reasons, therefore the techniques of suppressing particular dispersion components vary from each other. One can distinguish between a number of types of dispersion, such as modal, waveguide or material dispersion. Chromatic dispersion consists of two components. The first one comes from bulk material dispersion D_{mat}. The second one comes from waveguide

dispersion D_w, where the material and the waveguide dispersion are expressed, as follows:

$$D_{mat} = \frac{-\lambda}{c}\frac{d^2 n_M}{d\lambda^2} \tag{1}$$

$$D_w = \left(\frac{-\lambda}{c}\right)\frac{\partial^2[\mathrm{Re}(n_{eff})|_{n_M(\lambda)=Cons.}]}{d\lambda^2} \tag{2}$$

where n_m is the matrix index. Since waveguide dispersion can be anomalous and material dispersion normal, optimal dispersion design can be achieved by the suitable balance of particular dispersion components contributing to the total dispersion. To design a fiber with zero dispersion, it is necessary to optimize both: material properties, as well as the shape of the waveguide. There exists, therefore, a wavelength, at which total dispersion is equal to zero. Beyond this, the fiber exhibits a region of anomalous dispersion, which can be used for the compression of pulses in optical fibers.

To achieve a specific value of total dispersion, one must compensate material dispersion D_{mat} with waveguide dispersion D_w. The slope of D_w should be adjusted by optimizing the fiber's geometry in order to make it parallel to $-D_{mat}$. If the goal is to obtain flattened dispersion in a target wavelength interval, one must control D_w to make it follow a trajectory parallel to that of $-D_{mat}$. If material dispersion is linear in a target interval, a systematic approach can be used. Generally, this is the classical method of how to treat chromatic dispersion profiles using geometrical parameters in PCFs with successive iterations of structural parameters to improve the quality of the results.

3.2 Current state of the art

Due to unique dispersion flexibility, PCFs are considered as useful for achieving anomalous dispersion. They are used for the robust compensation of chromatic dispersion or dispersion-free transmission. There are several practical solutions to limit chromatic dispersion and to keep the initial width of optical pulses. One of the methods is to design fibers with zero dispersion. Resultant zero dispersion can be achieved by compensating material dispersion with waveguide dispersion. This operation is generally possible at a specific wavelength, so that the signal must be transmitted within a very narrow range of optical frequencies.

3.2.1 Dispersion compensating fibers

Zero dispersion is useful for low-speed systems, but can be undesired in high-speed transmission systems, since the phase match of all the frequency components can result in nonlinear effects. Another method of keeping a constant pulse width is to retain small normal dispersion in optical fibers and compensate it by using Dispersion Compensation Fiber (DCF), added at signal repeater. In general, chromatic dispersion compensators optically restore signals that have become degraded by chromatic dispersion, significantly reducing bit error rates at the receiving end of a fiber's span. A DCF is characterized by strong anomalous dispersion, which exactly compensates normal dispersion arising between repeaters. Many studies have been published about the design and optimization of chromatic dispersion in PCFs. They tend to shift zero-dispersion wavelengths or

minimum anomalous dispersion wavelength towards at the conventional band around 1550 nm, (known as C-band). Conventional dispersion compensating fibers are designed to operate at a specific wavelength, for example at 1550 nm, achieving negative value of at least hundreds ps/km/nm at the operating wavelength. Recently, the extension of operating bandwidth towards longer wavelengths is the area of interests, since short optical frequencies are more used in high-speed transmission systems.

PCFs are highly flexible for engineered dispersion. By manipulating the geometry design of the PCF (core diameter, normalized hole diameter, number of rings, hole defects), it is possible to achieve desired dispersion and losses required for specific applications. The interplay between chromatic dispersion and geometrical structure allows establishing a well-defined procedure to design specific predetermined dispersion profiles. This topic is described in many studies about the dispersion controllability.

One of the very first works with significant contribution to this topic is a work by Birks et al. (1999). The latest studies report new aspects related to the topic (for example the work of Haxha et al., the work by Liu et al. or finally the one by Razzak et al). The main topic addressed in those works is the ultra-flattened dispersion at a wide wavelength interval and at low confinement losses.

Premium DCF is demonstrated by Wu et al. (2008), where the negative dispersion value of –1350 ps/km/km at 1550 nm is achieved. Other designs aim to achieve dispersion in the wavelength range of about 1500-1625 nm. This could open a door for broadband dispersion compensation using PCFs.

3.2.2 Dispersion flattened photonic crystal fibers

Achieving a flattened dispersion curve is required for many telecommunication applications, in which we desire to have the same dispersion values for broad band utilization. For this purpose, some studies are focused on investigating various techniques of adjusting the PCF's geometry to obtain flattened dispersion characteristic. With this regard, a study presented by Liu et al. (2007) shows, how ultra-flattened dispersion curve could be achieved using elliptical holes. An optimized design of a PCF over ultra-wide band by replacing two rings of inner circular air holes with elliptical air holes is presented. The permitted dispersion fluctuation is 0.6–1.0 ps/nm/km within a broad band from 1000 nm to 1900 nm, which means over all: S, C, and L bands. Moreover, periodic structures having small core with large equal-sized air holes managed to shift zero-dispersion wavelengths towards shorter wavelengths.

Summarizing, the design process requires high attention to all important properties, such as flattened chromatic dispersion curve, effective mode area, confinement loss over broad bandwidth. In addition, designers should consider the complexity of new structure's fabrication process.

3.2.3 Doping technique for enhanced dispersion properties

The standard solid core PCF with hexagonal lattice and medium air-fraction volume exhibits chromatic dispersion characteristics far from the preferable ones for practical implementations. Doped cores can be used to enhance dispersion properties of IGPCF. The technique is based on doping of the central part of the SiO_2 core by the GeO_2 material. The germanium dioxide raises the refractive index of the doped region and hence modifies the waveguide properties of the PCF.

The dispersion behavior has been investigated for Highly Non-linear PCF (HNPCF), where the core's refractive index is increased by doping with high-index material, such as rare earth ions. The idea of doping the PCF's core with rare earth elements has been investigated. For example, an ytterbium-doped PCF can be used to achieve enhanced nonlinearities. The most widely used dopant in PCF is Germania – GeO_2, due to its intensified nonlinearities and enhanced photo-sensitivity. In fiber fabrication process, the refractive index of the doped core is determined mainly by the concentration of the GeO_2 ions embedded in the core. The accurate characterization of the dopant's location and its concentration in optical fibers is studied by Zhong et al. The dispersion dependence on the concentration of GeO_2 in the fiber's core is explained accurately by Hoo et al. (2004). Notice is hereby given that GeO_2 is a dopant commonly used for doping the core region for raising the refractive index, on the other hand, B_2O_3 or F are doping substances suitable for doping the cladding region that in turn lower the refractive index.

3.3 Shortcomings of existing solutions

The narrow bandwidth of operating wavelengths is considered as a limitation, in particular for systems with Wavelength Division Multiplexing. Therefore, recent studies focus on the ultra-low, ultra-flattened broadband dispersion over a wide spectrum of telecommunication wavelengths. PCFs can be exploited into this aim, since the large refractive index variation between silica and air permits to achieve significant waveguide dispersion over a wide wavelength range. PCFs with large air-holes have already been proposed in some studies about dispersion compensation.

Many DCFs uses the technique of doping their core with high-index material. This can result in high confinement losses, reaching even more than 1 dB/km, as indicated in catalogues of commercially available fibers. In addition, those fibers suffer from small effective mode area, since some DCFs have an extremely small core and concurrently high air fraction to enhance nonlinear evolution of spectral characteristics.

4. Simulation method

Huge possibilities of geometry manipulation and air-holes shapes arrangements have increased the complexity of numerical analysis of PCFs. The main objective of simulations is to study chromatic dispersion characteristics of IGPCF and HNPCF. Such structures demand efficient numerical methods to analyze them accurately. Thus, many modeling methods have been applied in this perspective, such as the plane wave expansion method, localized function method, finite element method, finite difference time domain method, finite difference frequency domain method, Fourier composition method or multipole method. The results presented in this work have been achieved by using the full-vectorial Finite Difference Frequency Domain method (FDFD), which was described in details by Zhu et al. (2002). This tool practically employs the same algorithm as the Finite Difference Time Domain (FDTD) method, the only difference between the two algorithms is that FDFD is a 2D solution, whereas FDTD is a 3D solution, which means that FDFD is easier for software implementation and meanwhile leads to the same numerical dispersion equation as that of the 3D-FDTD method.

For a given frequency, the numerical propagation constants and mode patterns can be calculated. The main geometrical quantities concerned: hole diameter d, the hole pitch Λ, and the core diameter, used in the implementation are displayed in Fig. 1.

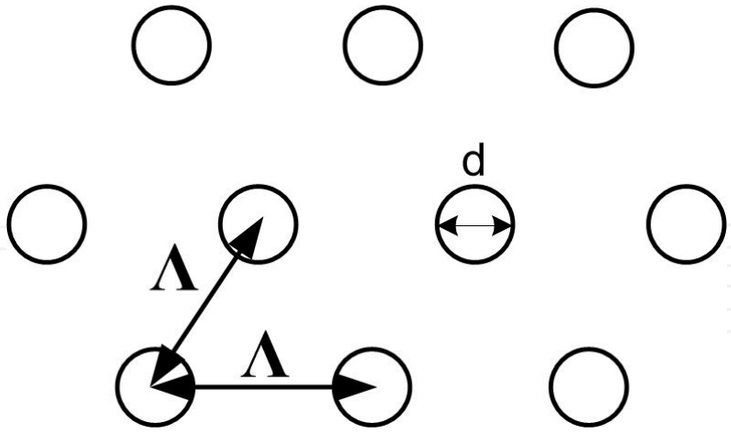


Fig. 1. Geometrical quantities describing PCFs.

In order to investigate the optical behavior of PCFs, the structure presented in Fig. 2 is used. It represents a HNPCF structure, where the core is doped with high-index material.

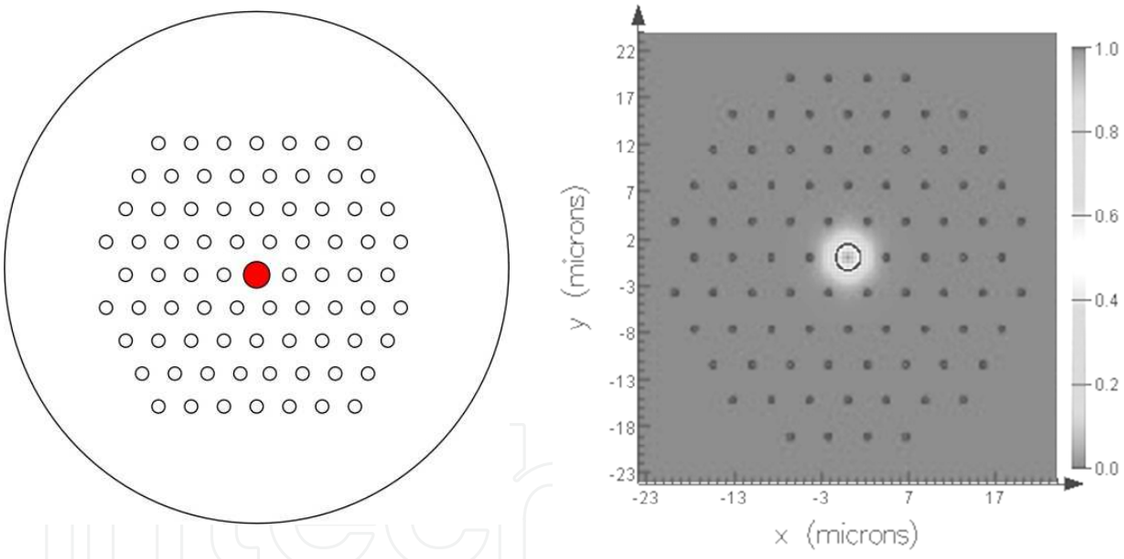


Fig. 2. Doped structure evaluated in terms of dispersion compensation (left) and the fundamental mode of the modeled PCF (right).

The basic flow of simulation is executed with several iterations to calculate the number of parameters and to obtain precise results. The simulation algorithm for parameters sweeping contains few steps: once the physical structure is created, the simulation parameters and mesh are set, as well as the monitors are defined, the simulation is run. The frequency domain information is available at any point of the cross-section of a modeled fiber.
In order to perform a series of simulations to investigate the change in measured intensity as a function of geometry or to perform any other systematic study, the built-in scripting environment is used. This scripting environment has many advantages, where one can

extract specific values of parameters or implement a required sweep in the structure and observe how chromatic dispersion or bending loss parameters are changed.

5. Simulation results

In order to understand the behavior of chromatic dispersion and loss in PCFs, an analysis has been proceeded to study the HNPCF with high-index doped core.

5.1 Dispersion in doped PCFs

The investigated HNPCF structure is specified in Table 1, where the cladding includes five rings of air holes and the core, which doped with high-index material, of which the refractive index is equal to 1.475. Relatively small air holes are preferred.

Parameter [unit]	Value
Pitch Λ [μm]	4.4
Hole's diameter d [μm]	Varied 0.6–2.2
Normalized hole diameter d/Λ [-]	Varied 0.1–0.5
Air-fraction refractive index [-]	1
Dopant's (core's) refractive index [-]	1.475
Silica glass refractive index (high-index cladding region) [-]	1.458
Propagating wavelength [nm]	1550
Core diameter [μm]	1.4
Effective index of cladding at 1550 nm	1.4582
Number of rings at the cladding Nr	5

Table 1. Structural parameters for the doped PCF presented in Fig. 2

Dispersion in nonlinear doped microstructured optical fiber, specified in Table 1, is shown in Fig. 3.

The doped PCF has a parabolic dispersion curve (in contrast to standard IGPCF, where dispersion shows linear increase with wavelength, which is presented in studies describing dispersion in PCFs). Usually, dispersion in fibers with a hexagonal lattice has a Zero Dispersion Wavelength (ZDW) at the O-band.

A general tendency in microstructured fibers is that both ZDWs are found at shorter wavelengths, when the fraction of air filling is increased or when the central defect is decreased.

Adjusting the geometrical parameters can be a tool to control the curvature of a dispersion profile. This can eventually lead to two closely laying ZDWs and very low minimum dispersion or, vice versa, to ZDWs far from each other, and flat dispersion curve. This mechanism shows a good agreement with the results achieved in this numerical analysis. Though, the second ZDW is located rather at longer wavelengths.

For the studied structure, the dispersion curve of HNPCF presented in Fig. 3 crosses the x-axis at two zero points, the first one appears at the shorter wavelength, usually at the O-

band or the E-band, whereas the second point is located at the longer wavelength, usually at the C-band or the L-band.

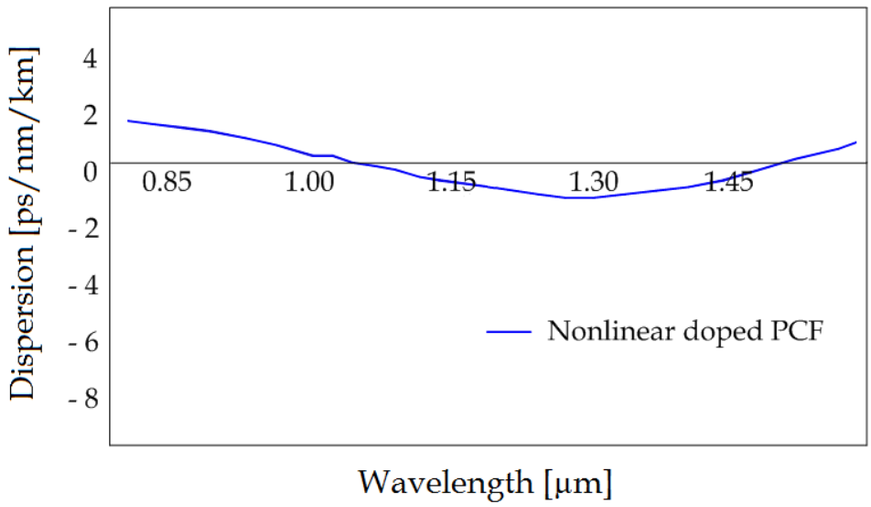


Fig. 3. Chromatic dispersion in regular solid-core PCF and modeled doped PCF.

The investigation focuses on the properties resulting from a doped core to control the dispersion in PCFs. The technique is based on doping the central part of the SiO_2 core by the GeO_2 material. The ZDWs are found at shorter wavelengths, when the fraction of air filling is increased and the central defect is decreased. Adjusting the geometrical parameters can rather result in different dispersion properties; the most mature designs assume the second ZDW being rather at longer wavelengths, since shorter optical frequencies are more used in high speed transmission systems.
The advantage of the studied structure is the flexibility of adjusting both: minimum anomalous wavelength and ZDW locations. As it is demonstrated below, such type of fibers is highly sensitive to geometrical parameters, as well as to the change of material index values. It also keeps an endlessly single mode characteristic of a solid core PCF.

5.2 Chromatic dispersion dependence on air-fraction volume

Results shown in Fig. 4 indicate a negative behavior of chromatic dispersion; the second ZDW is affected by the air fraction percentage.
With a decrease in hole diameter, it is possible to move the position of the second ZDW to higher wavelengths, reaching the C and L-band, with regard to current trends in systems using Wavelength Division Multiplex.

5.3 Chromatic dispersion dependence on core diameter

Similar results are achieved for the core diameter optimization and for varied refractive index. Parameters for the core diameter sweeping are presented in Table 2. For this purpose, all the parameters are fixed, as given in Table 2, while the core diameter is chosen to vary from 2.8 to 4.4 μm As far as core diameter is concerned, all the remaining parameters are fixed (with d/Λ being 0.3). As depicted in Fig. 5, the minimum dispersion value arises with the increase in core diameter.

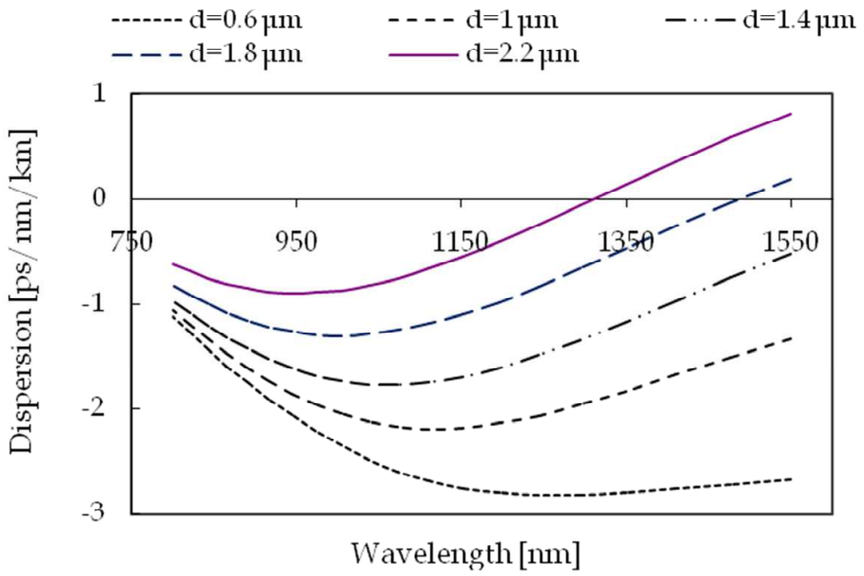


Fig. 4. Chromatic dispersion dependence on hole diameter.

Another conclusion, which reveals at Fig. 5, refers to the behavior of ZDW. We observe that greater value of a core diameter is responsible for ZDW achieved at longer wavelength. At the specific value of a core diameter (3.6 μm), the values of studied dispersion start to be positive.

Parameter [unit]	Value
Pitch Λ [μm]	4.4
Hole's diameter d [μm]	1.32
Normalized hole diameter d/Λ [-]	0.3
Air-fraction index [-]	1
Dopant's (core's) refractive index [-]	1.475
Silica glass refractive index (high-index cladding region) [-]	1.458
Propagating wavelength [nm]	1550
Core diameter [μm]	Varied 2.8– 4.4
Effective index of cladding at 1550 nm	1.4586
Number of rings at the cladding *Nr*	5

Table 2. Structural parameters for PCF doped in a small core.

5.4 Chromatic dispersion dependence on doping level

In order to precisely control chromatic dispersion, the effect of changing the dopant's refractive index (that can be practically achieved by changing the concentration of GeO_2

from 16 to 30 %) is further investigated. By the increase in refractive index, lower minimum dispersion in the area of negative values is produced.

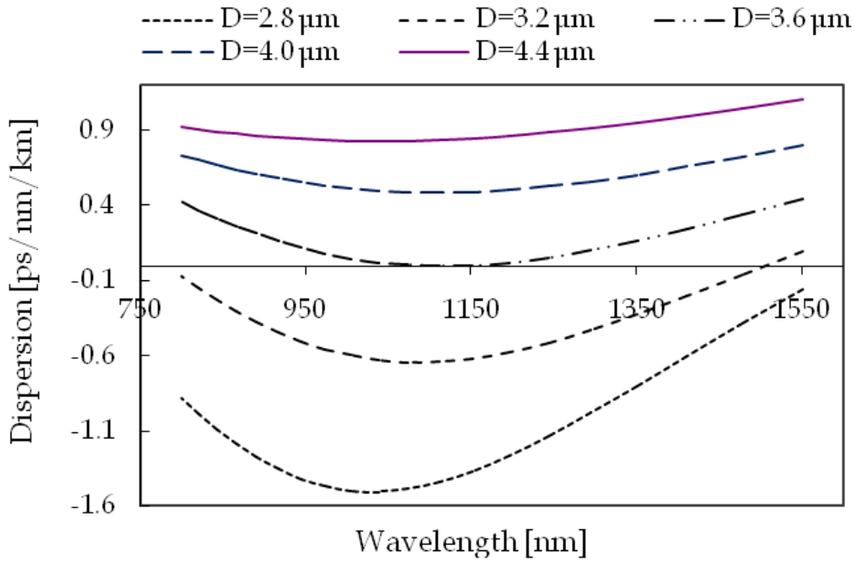


Fig. 5. Chromatic dispersion dependence on core diameter.

Fig. 6 combines the effect of the refractive index values varied from 1.472 to 1.49, in which a summarized impact over all: O, E, S, C, L bands is shown. Considering a specific wavelength, for instance 1550 nm, dispersion increases with refractive index of the doped core.

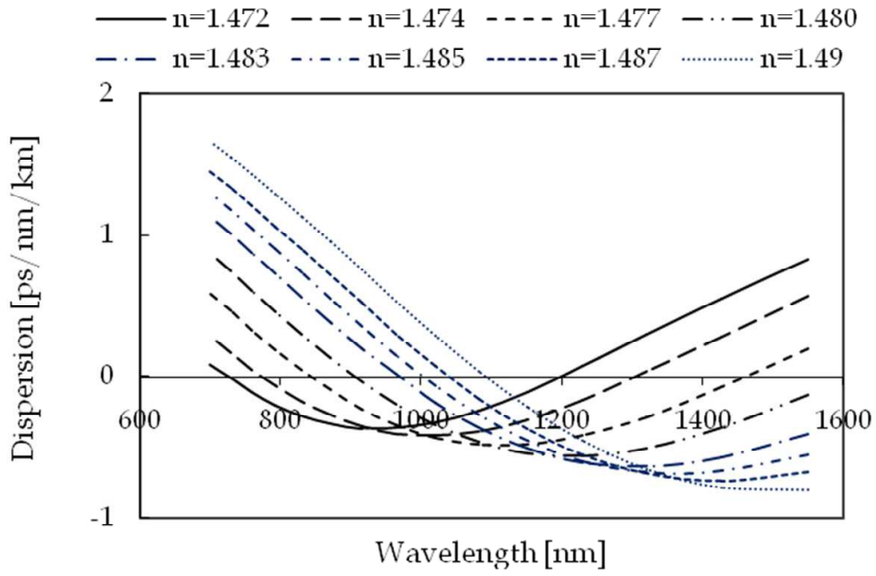


Fig. 6. Chromatic dispersion dependence on dopant material refractive index.

Extracted values of ZDW obtained for varied material refractive index are presented in Table 3.

Refractive index [-]	First ZDW [nm]	Second ZDW [nm]
1.472	728	1190
1.474	780	1320
1.477	835	1450
1.48	913	1556

Table 3. Location of first and second ZDW in the modeled PCF.

6. Design of PCF with ultra-flat chromatic dispersion

The combination of studied parameters could interplay with their effects to achieve optimal dispersion for telecommunication applications. This is generally considered as one of the major advantages of PCFs.

A PCF with flattened dispersion curve is required for telecommunication applications, in which we desire to have the same dispersion values for broadband utilization, in this case long-distance propagation with nearly zero dispersion in systems with Wavelength Division Multiplexing. The final goal is to optimize the structure to achieve flattened dispersion curve and dispersion values near zero. This could be done by finding the suitable configuration of the following parameters: hole diameter, core diameter, and selective doping.

The proposed structure is doped by using GeO_2. The fiber has three air rings of holes in the cladding. The doped core radius is 7.4 μm, which is relatively big compared to all above studied structures. Detailed description of the proposed structure is summarized in Table 4.

Parameter [unit]	Value
Pitch Λ [μm]	4.4
Hole's diameter d [μm]	1.32
Normalized hole diameter d/Λ [-]	0.3
Air-fraction index [-]	1
Dopant's (core's) refractive index [-]	1.48
Silica glass refractive index (high-index cladding region) [-]	1.458
Propagating wavelength [nm]	1550
Core diameter [μm]	7.4
Effective index of cladding at 1550 nm	1.465
Number of rings at the cladding Nr	3

Table 4. Structural parameters of HNPCF for achieving ultra-flattened dispersion diagram.

As it is observed in Fig. 7, the fundamental mode is trapped in the core. The fiber operates as a single-mode PCF. A special attention should be taken during the fabrication of the core, which is much greater than the doping region, as depicted in Fig. 7.

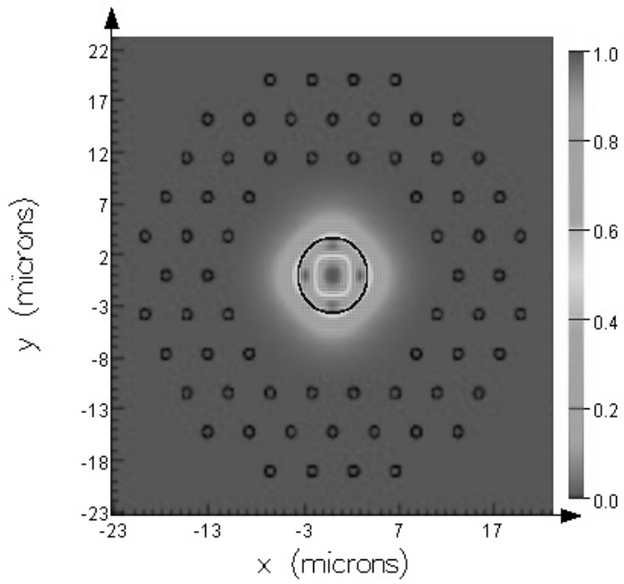


Fig. 7. The fundamental mode of the proposed near-zero ultra-flattened PCF.

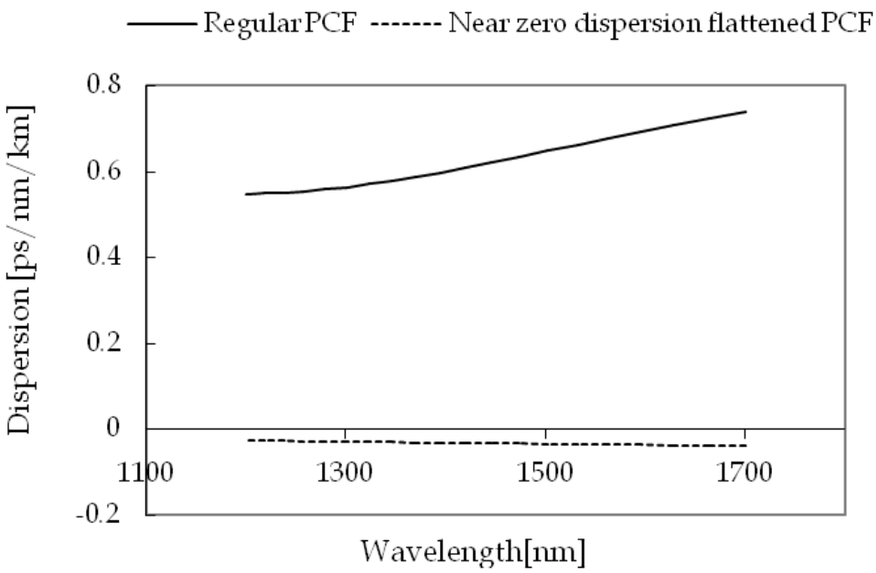


Fig. 8. Chromatic dispersion of the designed PCF compared to the regular IGPCF.

The achieved dispersion is ultra-flat with small negative values around –0.025 ps/nm/km. It can be observed that the chromatic dispersion is almost constant at a wide telecommunication wavelength range. The result is compared with the regular solid-core IGPCF. (As a reference, a standard structure made with medium-sized, pure silica core and

medium air-filling fraction is concerned). In Fig. 8, a comparison between the dispersion values of the standard IGPCF and the designed structure is presented.

7. Conclusion

New fiber structure with near-zero ultra-flattened is proposed. It is suitable for broadband utilization in transmission systems. Before this, many fibers have been examined and many improvements have been applied to the studied structures. It is described how to control the location and shape of the chromatic dispersion curves. An investigation is carried out to study the PCF with high-index core material, in which a parabolic curve is evaluated in terms of potential ZDWs.

Investigated PCFs showed higher flexibility in fiber design. A new fiber structure is introduced and investigated. The bandwidth, in which anomalous dispersion is achieved, is getting wider with decreasing air fraction. By the increase in hole diameter, the second ZDW is extended till the U-band. Lower minimum dispersion values are achieved by the increase in doping region diameter.

Utilizing all the previous results of the interplay between chromatic dispersion on one side, and geometrical parameters as well as refractive index on the other side, has provided a well-defined procedure to design ultra-flattened and ultra-low chromatic dispersion profile.

HNPCF is doped with high-index material (dopant GeO_2) with the refractive index of 1.48 and only three air rings in the cladding. The achieved dispersion results were ultra-flattened with very small negative dispersion values: –0.025 [ps/nm/km] over the telecommunication band. The fiber is suitable for broadband zero-dispersion propagation of optical signals in high-speed transmission systems.

The future study will focus on achieving flattened and high anomalous chromatic dispersion for telecommunication applications. For example, the insertion of liquids in PCFs is promising for achieving optimal chromatic dispersion and nonlinear effects. Another goal is to optimize the studied structures without doping. Structures matching the characteristic of ITU-T standard fibers will be studied.

Last but not least, the future research should be highlighted on the recurrent optimization of algorithms to be developed.

8. Acknowledgment

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This book presents a comprehensive account of the recent progress in optical fiber research. It consists of four sections with 20 chapters covering the topics of nonlinear and polarisation effects in optical fibers, photonic crystal fibers and new applications for optical fibers. Section 1 reviews nonlinear effects in optical fibers in terms of theoretical analysis, experiments and applications. Section 2 presents polarization mode dispersion, chromatic dispersion and polarization dependent losses in optical fibers, fiber birefringence effects and spun fibers. Section 3 and 4 cover the topics of photonic crystal fibers and a new trend of optical fiber applications. Edited by three scientists with wide knowledge and experience in the field of fiber optics and photonics, the book brings together leading academics and practitioners in a comprehensive and incisive treatment of the subject. This is an essential point of reference for researchers working and teaching in optical fiber technologies, and for industrial users who need to be aware of current developments in optical fiber research areas.

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