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Dispersion Compensating Fibres for Fibre Optic Telecommunication Systems

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1. Introduction

Chromatic dispersion (CD) of optical pulses in an optical fibre influences their width. It refers to changes in propagation of particular frequency components contained in optical pulses causing extension of optical pulses. The fibre reach is then significantly limited, unless signal regenerators are used. Because the pulse spread degrades optical systems, it is necessary to prevent its origination or to eliminate its results. CD ought to be suppressed or one shall prevent its origination by specialty optical fibres, including both conventional and micro-structured optical fibres (MOF). To keep the pulse length nearly constant, it is possible to use Dispersion Compensating Fibre (DCF) that shall be installed at the regenerators that provide amplification, renewal of timing and pulse duration. DCFs have negative dispersion parameter; CD accumulating between regenerators is then suppressed. Consequently, bit error rate could be improved and the fibre reach could be extended [1].

Photonic Crystal Fibres (PCF) could be a suitable solution for the problem of CD in high-speed transmission systems, especially those using Wavelength Division Multiplexing (WDM) to increase the symbol rate [2].

We systematize design approaches for specialty dispersion-tailored optical fibres in order to offer a guideline to flexibly design optical fibres used in telecommunications whose optimized CD is a key property. Last but not least, we present selected fibre designs prepared in last few years, including CD plots and information about structural parameters.

The knowledge about how to design fibres could be useful to design optical fibres, such as for example a submicron flat CD compensating fibre. In addition, fluoride compounds, as compared with silica glass, exhibit higher effective refractive index, the wider spectrum of working wavelengths (λ) or lower insertion losses. Additives using these materials are

promising for extending the application towards infrared region, where fluoride glasses are usually transparent.

2. Fibres with optimized dispersion [3]

DCFs could regenerate signals that are spread as a consequence of CD. This practically means that the bit error rate at the receiver's side could be improved or the spaces between adjacent symbols could be reduced. As a result, potential bit rate could be increased. One of the approaches how to deal with CD is to use zero CD fibres, offering near zero CD at the operating λ s. (It shouldn't be exactly zero because of Four Wave Mixing problem occurring when propagation is with zero dispersion and the phases of all the frequency components are matched). Another approach is to use already mentioned DCFs at the signal regenerators. CD tailoring fibres could work at some λ , e.g. at 1.55 μm , where they could have negative value of CD being few hundred picoseconds (ps/nm/km), which expresses the delay between the slowest and fastest frequency component measured at the distance of 1 km, assuming the source of radiation emitting the spectrum of 1 nm. Sample compensating fibre was published in Refs. [4] and [5]. Very low CD parameter is observed whose properties could benefit in compensation of CD accumulating in some optical network. An unsolved problem seems to be relatively narrow window of λ s. Such a fibre could then compensate CD in just one λ channel of a WDM system [3].

Resultant CD is a balance between waveguide and material component. In order to obtain flat CD, the evolution of waveguide dispersion has to be exactly opposite to the one of material dispersion, which means that both ought to be optimized at each channel step by step. The situation is simple when material dispersion is linear upon λ . Then, one could employ an algorithmic approach with iterations to calculate and precisely adjust the CD at each λ . A very important assumption is that the balance between both dispersion components could be a very useful tool in designing fibres for CD tailoring by optimizing material dispersion (through the material properties) and waveguide dispersion (as a result of optimization of the shape of the waveguide) [3] [6].

2.1. Dispersion compensating fibres [2]

When a compensating fibre works at some λ , optical symbols ought to be transmitted at small spectrum of light waves, without multiplying the bit rate in many channels. Such narrowband fibres can have very low value of CD that is possible without using additives (e.g. germanium dioxide). In Ref. [7], it could be found that CD of -18 ns/nm/km is possible. Other works concentrate rather on the optimization of the structural parameters of MOFs to obtain flat CD diagram. Microstructured fibres offer much greater flexibility because geometry could be optimized not only through the core and cladding diameter, but also by changing the air filling fraction, and the lattice pitch including its arrangements. In Ref. [8], flat CD over all the telecom bands is shown [2].

Index guiding MOFs (the one without the central inclusion, having solid core) offer high flexibility in CD compensating fibres design. For example microstructured based DCFs could have dual cores [9] or they could be doped [10]. Negative value of CD parameter in DCFs with dual core structure could also be combined with the idea of making some rings with smaller holes [7][10]. Such a DCF with low CD parameter in broad telecom band is shown in Ref. [11], in addition, a square lattice (with the defining angle of 90°) was proposed. The performance of DCFs with the concentric cores could be increased by using germanium dioxide in the core [12]. The relation between the amount of additives and resultant CD is shown in Ref. [13]. Some other substrates could be used to lower the effective index (n_{eff}), such as for example fluorides [14]. On the contrary, germanium dioxide raises n_{eff} . The key feature is not to raise or lower a certain index, but to create large index contrast between the fibre's core index and its n_{eff} of the cladding [2].

Fibres with flat CD, i.e. those having low value of CD in many λ channels concurrently are often considered as wideband fibres, but they can't be used to compensate CD in all λ channels at once, because accumulated CD in each WDM channel is different. They are rather suitable to compensate CD at one channel, which can be selected from the wide range of λ s that are compatible with the used DCF. Real wideband fibres should compensate CD at every λ channel at the same time. They must have CD exactly opposite to dispersion in each channel. In Ref. [15], it is shown that larger lattice pitch in the 1st ring of holes is responsible for the CD slope that must be optimized for this purpose. In addition, the hole radius in the 1st ring should be larger to enhance dispersion. CD slope property is studied in Ref. [16] in the context of wavelength division multiplexing. Another slope compensating DCF is shown in Refs. [2] and [17].

2.2. Zero dispersion wavelengths in DCFs

Because a great part of MOFs have parabolic wavelength evolution of CD and the minimum CD at low values, those fibres can have two zero-CD wavelengths (ZDW). The 1st ZDW is the one utilized at visible wavelengths, whereas the longer ZDW is used at telecom wavelengths [18]. Such Highly Nonlinear PCF (HNPCF) could exhibit positive slope at 1st ZDW and negative slope at 2nd ZDW, as shown in Ref. [19]; the 1st ZDW was at 900 nm, the 2nd one at the λ of 1.6 μm .

The high index difference between the air-filled microstructure and pure or doped silica core enables tight mode confinement resulting in a low effective area and, thereby, a non-conventional behaviour of CD. Modifying the periodic cladding (i.e., hole-sizes, lattice pitch), the waveguide dispersion and the origination of ZDWs are influenced, keeping the fibre still in single-mode operation regime [20]. Then, the strong wavelength dependence in the characteristics of the fibre will be used to determine either huge CD with large slope or nearly-zero flat CD.

The bandwidth, at which MOFs are designed to have zero CD, could be divided into three categories: working in the region between 0.55 μm and 1 μm , where 1st zero-CD point could be determined; another region between 1 μm and 1.2 μm , where 1st or 2nd ZDW could be found. The 3rd region, starting at 1.2 μm and going up to longer λ s, is used to create the 2nd zero CD

and is not available for the 1st zero CD. An overview of the obtainable ZDWs as a function of MOF's structure was shown in Ref. [21].

Both core size and the radius of holes exhibit significant influence on the location of both ZDWs. Increasing core size tunes the ZDW to longer λ . The increase in air percentage in the cladding could extend the origination of the 1st ZDW at longer wavelengths and the 2nd ZDW at shorter λ s (i.e. less negative CD is obtained for larger air-filling fraction).

2.3. Dispersion flattened fibres and wideband fibres [2][3]

Some compensating fibres could work at short spectrum of λ s. When a compensating fibre works at a certain λ , optical pulses can be transmitted using one or – in general – low amount of WDM channels. As it has already been mentioned above, MOFs are suitable for designing the compensating fibres because they allow huge index contrast and offer many parameters to be optimized (core size, hole radius, lattice pitch, amount of rings of holes) in order to optimize waveguide dispersion [2].

Currently, flat CD fibres could for example be referred to as near zero CD transmission medium. In Ref. [22], a DCF made of pure (undoped) material is shown. Advanced DCFs with flat CD property over broad spectrum of working λ s could be found in Ref. [23]. An interesting fibre with CD parameter close to zero with CD fluctuations less than 0.5 ps in S to L bands is shown in Ref. [24]. Results were obtained by careful optimization of holes in particular rings. To reduce losses, it is often required avoiding doping the MOF's core. Instead, one could consider using octagonal [25] and decagonal [26] lattice, or more sophisticated lattice arrangements [2].

Recent analyses concentrate on the low, flat CD over telecommunication λ s for any telecom wavelength compensation. The value of CD and the width of the working range is a compromise. A DSF could have large negative CD value, but for medium-wide wavelength range, or, acceptable CD parameter, but designed for very broad spectrum of λ . Currently, the strongest demand is to design DCFs mainly for C and L bands, where modern WDM systems can work.

The idea how to obtain flat CD properties is to tune the 1st ZDW to shorter λ s and the 2nd ZDW to longer λ s, having little negative CD over the whole bandwidth at the same time. Practically, predicted CD diagram is a wide parabola. Considered properties are related to the diameter of the core and the radius of the holes in particular rings. Both were found to have different impact on the origination of each ZDW. There are requirements to locate the zero CD point at the λ of 1.55 μm or, in general, in the C-band [8]. Changing the air filling fraction and lattice pitch is not the only idea that could be used to optimize CD. For example elliptical holes instead of circular holes exhibit potential low and very stable CD properties, i.e. 0.6-1 ps/nm/km in the range from 1 μm to 1.9 μm [3].

Finally, there are a few examples that are worth to be noticed: a DCF in Ref. [27], with CD parameter being -1350 ps/nm/km at 1.55 μm ; another one in Ref. [28] has CD of -440 to -480 ps/nm/km at the band of 1.5-1.62 μm [3].

3. State of the art

The employment of the considered fibres is mainly in high-speed transmission systems using wavelength division multiplexing and signal recovery, offering transmission rates of even more than 1 Tb/s, where it is proved that non-optimized CD could destroy the pulse spreading, but as well it could generate some nonlinear effects, such as four wave mixing, among others. Although the properties of the fibres significantly differ from one another, the techniques used for optimized CD could be systematized so that one could design a fibre with desired CD value and slope at a specific λ .

Understanding of the mechanisms governing CD tailoring is necessary not only permits for the fibre design, CD suppression and avoidance, but also to predict the potential manufacturing tolerances. There are a few techniques used to obtain the expected CD and we describe them in more details in the following sections.

3.1. Fibre designs [1]

One of the techniques applied is to dope the fibre's core. By inserting small doped inclusion in a MOF's core, the index contrast with result in much larger mode confinement. Because the waveguide dispersion is related to it and because the length of propagated light waves is of the range that is comparable to the core size, the inserted region will be responsible for very low waveguide dispersion component.

There is another technique that could be used to optimize dispersion, it assumes to inject some liquids into the microstructured holes. In Ref. [29], the 4th ring of holes is doped by using liquids for this purpose. But liquid's properties are strongly dependent on temperature, which means that constant temperature must be ensured. This means that such a fibre could for example be used for some experiments in laboratory conditions (e.g. sensors), but they can't be used in outdoor installations of telecommunication systems [1].

Germanium dioxide is very often used to raise the effective index. In Ref. [13] and [30], the idea how to use it to dope the microstructured fibre's core is described in details. But this solution is not perfect in terms of effective area of the mode which is rather small in the doped fibres, as well as from the perspective of increased attenuation caused by material absorption, which is high for germanium dioxide [1].

Another technique to be described and systematized is the one using air holes located close to the fibre centre. The 1st mode could be confined within the core by the index contrast, and the effective diameter of a mode is then usually small enough to control CD. Stronger confinement could be obtained in a MOF using other type of a lattice, like for example octagonal, decagonal or spiral.

An alternative way, how to control the effective index, is to have core defects. A "defect core" is usually understood as one allowing light coupling to some other regions by some imperfection that is introduced intentionally. This technique uses weak interactions between the core-guided mode and a mode localized in an intentionally introduced defect of the crystal.

Finally, the idea of concentric cores could be considered. What feature in dual core technique is responsible for low CD? It is large value of n_{eff} produced by significant asymmetry between the two cores where light is coupled. Light is propagated in both cores concurrently. Dual cores are responsible for the phase matching at a certain λ , and consequently at this wavelength large CD parameter is obtained.

Low value of CD parameter is possible in concentric cores. They could be obtained by removing [7],[10] or reducing [7],[31] the air fraction in some rings of holes [1].

There are many aspects that could influence resultant CD; it could be coupling modes and the phase matching wavelength, at which CD control is possible, could be obtained in many ways, for example by fibre bending. We found these conclusions as interesting, because many works assume that the most important consequence of bending a fibre is increased attenuation. It could be shown that large negative value of CD parameter could be the accompanying process.

3.2. Extension of transmission band towards infrared – Fluoride fibres [32]

Dealing with the structural parameters of MOFs is a solution to find optimal CD. They could be enhanced by very careful optimizing the material composition. For example fluorides could be used as additives, but they could also be used as a background material instead of silicon dioxide, which could be evaluated as significant progress in the field [32]. The fluorides have low effective index, broad range of λ s and low attenuation. One could consider the use of BaF_2 , CaF_2 and more advanced ZBGA (ZrF_4 - BaF_2 - GdF_3 - AlF_3) or ZBLAN (ZrF_4 - BaF_2 - LaF_3 - AlF_3 - NaF) [32]. In addition, because those materials are composite, it is possible to change their composition in a compound in order to obtain n_{eff} value or its slope in the investigated area of λ . Last but not least, these materials are transparent in infrared region (as well as in the telecommunication bands) which makes them interesting for some applications in sensors. The properties of fluorides allow using them in MOFs [33]. They would lower the effective index of the cladding or the index at the second, larger concentric core. It is usually combined with doping the main core by using germania. This idea could be considered as a significant progress in fibre optic technology. Then a fibre with a W-type profile or refractive index could be created. For example, the core doped by using germanium dioxide would exhibit the n_{eff} of about 1.48 and concurrently the cladding index doped by using F- SiO_2 would exhibit the index of about 1.43. Similar solution (in general modified W-type index profile fibre) could be employed in systems with WDM [32],[34].

Material and structural parameters are key features in order to obtain exact CD at each λ , but the accuracy and quality of production could become a critical issue, especially in submicron fibres whose small holes with the diameter being less than one micron is problematic for some manufacturing technologies. All this combined with the application of new materials that should be processed in different way compared to siliceous materials could result in both attenuation and CD properties far from the expectations [32].

At the telecommunication band both ZBLAN and ZBGA showed similar attenuation properties like the one of silicon dioxide, but their CD properties significantly differ [35], in addition fluorides have different mechanical properties and they have to be fused at different temper-

ature than temperature for silica. The theoretical attenuation could even be of 0.01 dB/km, in the range from 0.3 μm to 4.3 μm . The n_{eff} in telecom band is 1.47 – 1.52 [32, 36].

4. Design approaches

To describe propagation of light in a given optical glass, we could consider the constant of propagation of a wave that is related to the phase variation [32]:

$$k = (\beta - j\alpha) \tag{1}$$

The real part β and the imaginary part ω could be specified [37]:

$$\beta = \omega \sqrt{\frac{\mu\epsilon}{2} \left[\sqrt{1 + \left(\frac{\sigma}{\omega\epsilon}\right)^2} + 1 \right]} \tag{2}$$

$$\alpha = \omega \sqrt{\frac{\mu\epsilon}{2} \left[\sqrt{1 + \left(\frac{\sigma}{\omega\epsilon}\right)^2} - 1 \right]} \tag{3}$$

Where ω is angular velocity, σ is conductivity, a μ is permeability and ϵ is permittivity. Because MOFs are dielectric it could be assumed that:

$$\left(\frac{\sigma}{\omega\epsilon}\right) \ll 1 \tag{4}$$

Both real and imaginary part of propagation constant in (3) could be simplified to a form:

$$\beta = \omega\sqrt{\mu\epsilon} \tag{5}$$

$$\alpha = 1 \tag{6}$$

MOFs could be described by an effective index n_{eff} which expresses “the refractive index at the boundary of two entities”, which in this particular case are the core and the cladding [32]:

$$n_{\text{eff}} = \frac{\beta}{k_0} \tag{7}$$

β is real part of the constant of propagation of core, k_0 is the constant of propagation in vacuum. Propagation constant depends on λ , it could be written that:

$$k = \frac{2\pi}{\lambda} \quad (8)$$

Group velocity that integrates optical waves in an “envelope” could be considered to describe its velocity. It refers to CD and is less than the speed of electromagnetic wave in vacuum [32]:

$$v_g = \frac{\partial \omega}{\partial k} = \frac{c}{\sqrt{1 + \frac{\omega^2 \lambda^2}{4\pi^2 c^2}}} \quad (9)$$

Then group delay τ_g could be calculated as time necessary for the propagation of wave to certain distance with velocity of v_g (9):

$$\tau_g = \frac{1}{v_g} \quad (10)$$

In general, chromatic dispersion CD is known as the dependence of group delay τ_g on the wavelength λ , at which the signal is transmitted [38]:

$$CD(\lambda) = \frac{\partial \tau_g(\lambda)}{\partial(\lambda)} \quad (11)$$

In simulations it is more suitable to use material dispersion equation described by using Sellmeier approximation. CD equation suitable for Sellmeier approximations is following [39]:

$$CD(\lambda) = -\frac{\lambda}{c} \frac{\partial^2 \text{Re}[n_{\text{eff}}]}{\partial \lambda^2} \quad (12)$$

Designs of MOFs could be calculated by Finite-Difference Frequency Domain (FDFD) method. The distribution of light could be calculated by discretizing electric (13) and magnetic (14) field, it is described in Refs. [32, 40], and [41]:

$$(\nabla_t^2 + k_0^2 \epsilon_r) \mathbf{E}_t + \nabla_t (\epsilon_r^{-1} \nabla_r \epsilon_r \cdot \mathbf{E}_t) = \beta^2 \mathbf{E}_t \quad (13)$$

$$(\nabla_t^2 + k_0^2 \epsilon_r) \mathbf{H}_t + \epsilon_r^{-1} \nabla_t \epsilon_r \times (\nabla_t \times \mathbf{H}_t) = \beta^2 \mathbf{H}_t \quad (14)$$

k_0 is wavenumber in free space, β is real part of the propagation constant, ϵ_r is dielectric constant as in (5). The FDFD method uses the discretization scheme shown in Ref. [42][32].

FDFD is used in many commercial simulators of mode distribution and n_{eff} calculators. In most of them, it is possible to use user friendly graphical interface, but when a very accurate result is demanded, many iterations ought to be done by creating a loop using an appropriate scripting language. We use a mode solver from the Lumerical Inc. When the fibre's cross section is proposed and the simulation parameters and monitors are set, the simulation is run [3].

Creation of realistic models of sophisticated optical glasses is an interesting feature. To introduce materials to the simulator, we used the Sellmeier approximation [32, 43],[44]:

$$n^2(\lambda) = A + \sum_i \frac{B_i \lambda^2}{\lambda^2 - C_i^2} \quad (15)$$

where A, B_i, C_i are coefficients referring to index n . As a result, the wavelength evolution of refractive index could be plot by using the Sellmeier equation. The coefficients for the expanded version of Sellmeier equation (16) could found in [32][45]:

$$n^2 - 1 = \frac{B_1 \lambda^2}{(\lambda^2 - C_2^2)} + \frac{B_3 \lambda^2}{(\lambda^2 - C_4^2)} + \frac{B_5 \lambda^2}{(\lambda^2 - C_6^2)} \quad (16)$$

where $B_{1,3,5}, C_{2,4,6}$ are material constants and λ is wavelength.

5. Exemplary results

In this section, we present some selected fibre designs covering the wide area of telecom photonic fibres for CD tailoring, such as DCFs with large negative CD parameter, wideband fibres or slope compensating fibres, or fibre designs suitable for CD prevention, such as near zero CD fibres. We employ different design approaches and optimize them based on parametric investigation.

5.1. Dual core dispersion compensating fibre with large negative dispersion parameter [1]

A concentric core DCF based on microstructured optical fibre is proposed [1]. There is an assumption for the proposed structure to keep the 1st mode in a central core over the wide working spectrum of λ and in order to obtain low CD at 1.55 μm , and with low theoretical losses. The refractive index is optimized by making smaller the hole diameter in the 2nd ring. The design is specified in Table 1, the cross section is shown in Figure 1 [1].

Quantity [unit]	Value	Value	Value	Value	Value
Lattice pitch Λ [μm]	1.55	1.52	1.50	1.48	1.45
Minimum D at 1.55 μm [ps/nm/km]	-1010	-1180	-1300	-1460	-1690
Core index [-]	1.44	1.44	1.44	1.44	1.44
Theoretical loss [dB/cm]	$9 \cdot 10^{-10}$	$7 \cdot 10^{-10}$	$3.8 \cdot 10^{-7}$	$3.8 \cdot 10^{-4}$	$7 \cdot 10^{-2}$
Full width at half maximum [nm]	142	132	129	125	122
Hole diameter d_1 [μm]	1.33	1.34	1.314	1.27	1.23
Hole diameter d_2 [μm]	0.55	0.54	0.574	0.63	0.67
Hole diameter d_3 [μm]	1.35	1.35	1.2	1.04	0.92
Number of rings [-]	6	6	6	6	6

Table 1. Parameters of a dual core MOF for CD suppression [1].

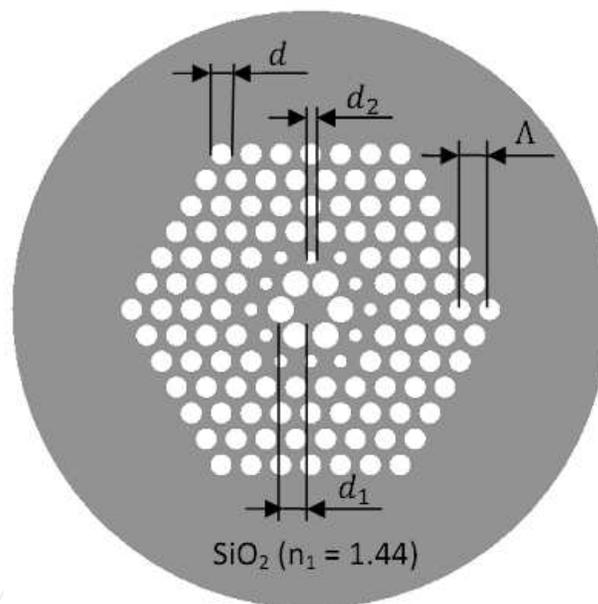


Figure 1. Structural parameters and the cross section of a dual core MOF for CD suppression purposes [1].

CD of the considered fibre is shown in Figure 2. Obtained CD parameter was -1460 ps/nm/km. The designed fibre work in the C-band, and the lowest CD is at 1.55 μm . Theoretical losses are $3.8 \cdot 10^{-4}$ dB/cm. It could be concerned as one of the advantages of the MOF, when we have a look at losses presented for some other fibres [1].

In order to obtain very accurate results, a number of iterations were performed to find the most suitable structural parameters of a fibre. One could conclude that smaller holes in the 3rd ring, and concurrently larger radius of holes in the 2nd ring could result in improved CD properties (Figure 3). Optimized solution could be found in Table 2 [1].

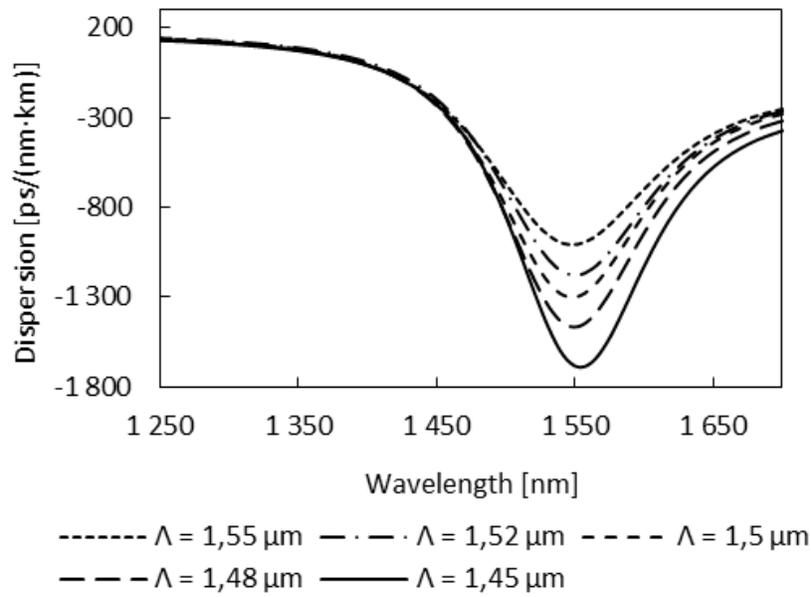


Figure 2. Chromatic dispersion in a dual core MOF for CD suppression at 1.55 μm [1].

Quantity [unit]	Value	Quantity [unit]	Value
Minimum CD [ps/nm/km]	-3290	Lattice pitch Λ [μm]	1.45
Core index [-]	1.44	Hole diam. d_1 [μm]	1.23
Theoretical losses [dB/cm]	7.50	Hole diam. d_2 [μm]	0.73
Number of rings [-]	6.00	Hole diam. d_3 [μm]	0.86

Table 2. Specification of parameters for dual core MOF for CD suppression [1].

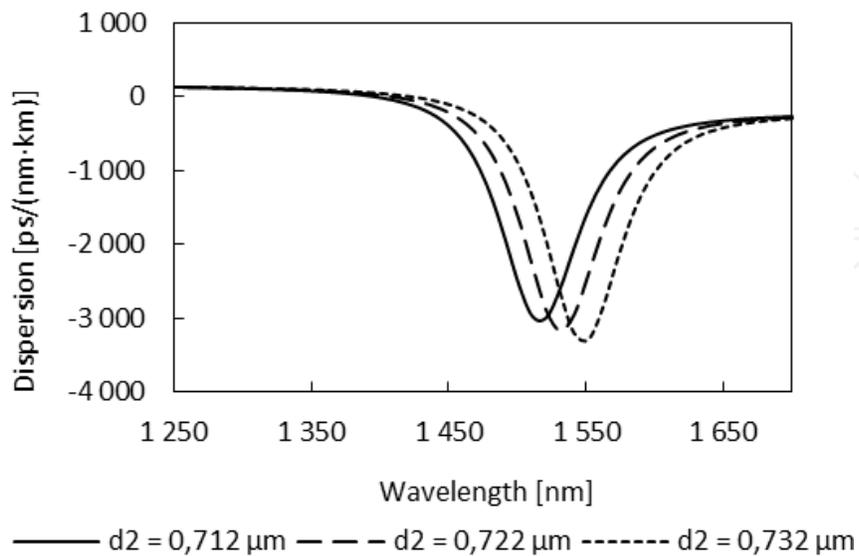


Figure 3. Dispersion in proposed dual core microstructured DCF [1].

In Figure 3, it could be observed that λ at which there is minimum CD is function of normalized hole diameter d/Λ of the holes; CD is mostly sensitive to the holes located in the 2nd ring. To move the operating λ towards 1.5 μm , one has to increase the size of the holes in this ring. Concurrently, the value of lowest CD is less. Summarizing, a one km long section of the designed DCF should be sufficient to tailor CD in a network that is created by using 75 km long conventional SMF with CD parameter being 17 ps/nm/km, (this value is in agreement with the recommendation of ITU-T for SMFs). The insertion losses of such a CD compensator are about 0.04 dB [1].

5.2. DCF with optimized dispersion slope [3]

Another design is done with the scope on fibres that could compensate CD in each channel of a system using wavelength multiplexing. It means that the fibre should be wideband, and its CD mustn't be flat, but it should have exactly opposite CD to CD of a fibre that is used in a WDM system. The proposal is shown in Figure 4 and in Table 3 [3].

n_{eff} [-]	1.47	Hole diameter [μm]	3.64
Core index [-]	1.48	Normalized hole diameter d/Λ [-]	0.58
Core size [μm]	4.46	Number of rings [-]	5

Table 3. Structural parameters of the HNPCF with dispersion evolution opposite to one in conventional MOF [3].

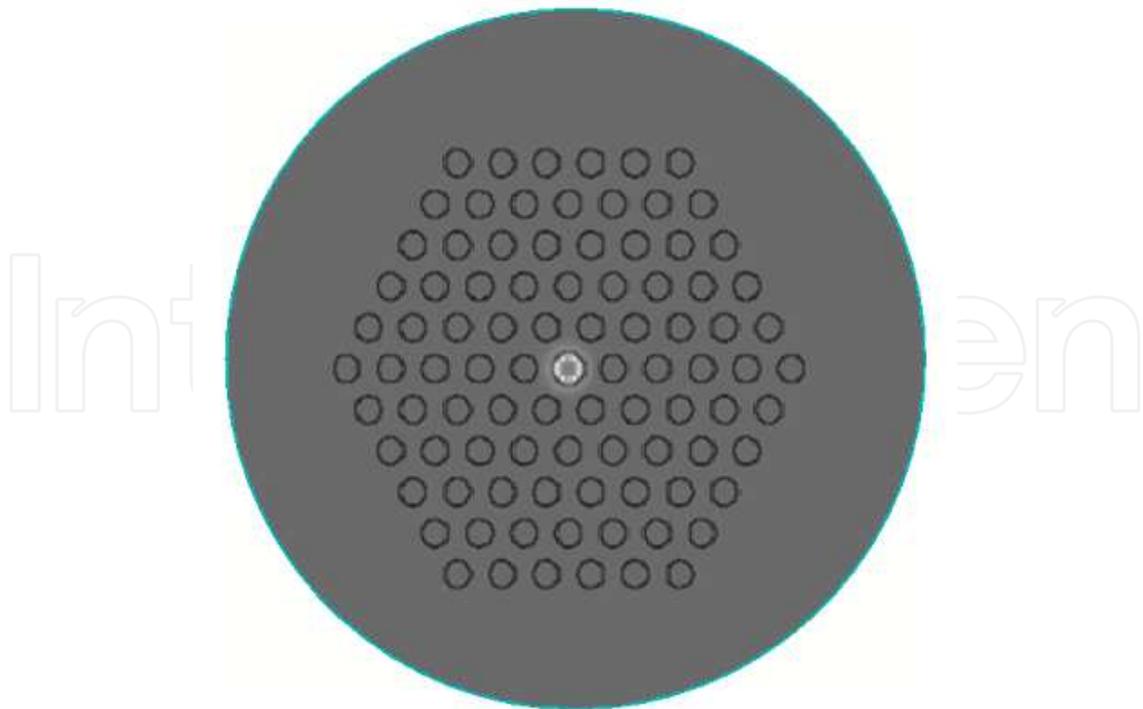


Figure 4. Cross section of a MOF with negative CD parameter [3].

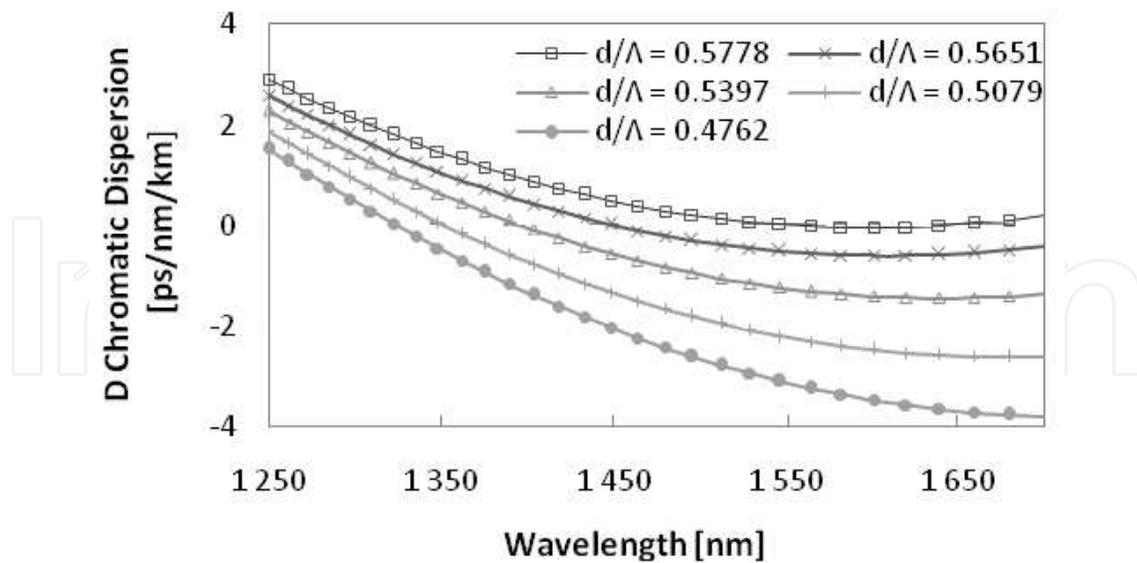


Figure 5. Reversed CD slope of the proposed DCF [3].

From Figure 5 it could be concluded that CD is reversed CD of conventional MOFs. The fibre is wideband. It could be optimized in terms of larger values of CD parameters, for example to exactly match CD evolution of conventional fibres. One shall also pay attention to the fact that larger d/Λ would result in multimode operation [3].

5.3. Dispersion flattened fibres and wideband dispersion compensating fibres [1][3]

A MOF with flat CD is demanded in design of transmission fibres (not suppression fibres) where it is d to have identical CD at each λ channel. Such a fibre could be doped in the core by using germania. The proposed core diameter could be $7.4 \mu\text{m}$. In Figure 6, the 1st mode is kept in the core and the fibre is single-mode. Manufacturing of the MOF's core could be challenging, because of huge doping area; the fibre has large mode area. The proposed geometry is described in Table 4 [3].

Hole diameter d [μm]	1.32	Silica index [-]	1.46
Lattice pitch Λ [μm]	4.4	Propagating λ [μm]	1.55
Normalized hole diameter d/Λ [-]	0.3	Core size [μm]	7.4
Air index [-]	1	Effective cladding index at $1.55 \mu\text{m}$	1.47
Core index [-]	1.48	Number of rings [-]	3

Table 4. Structure parameters for HNPCF flattened CD curve [3].

Obtained CD property could be evaluated as flat and oscillating around the value of -0.025 ps/nm/km . In Figure 7, comparison of CD in conventional MOF and the designed fibre is shown [3].

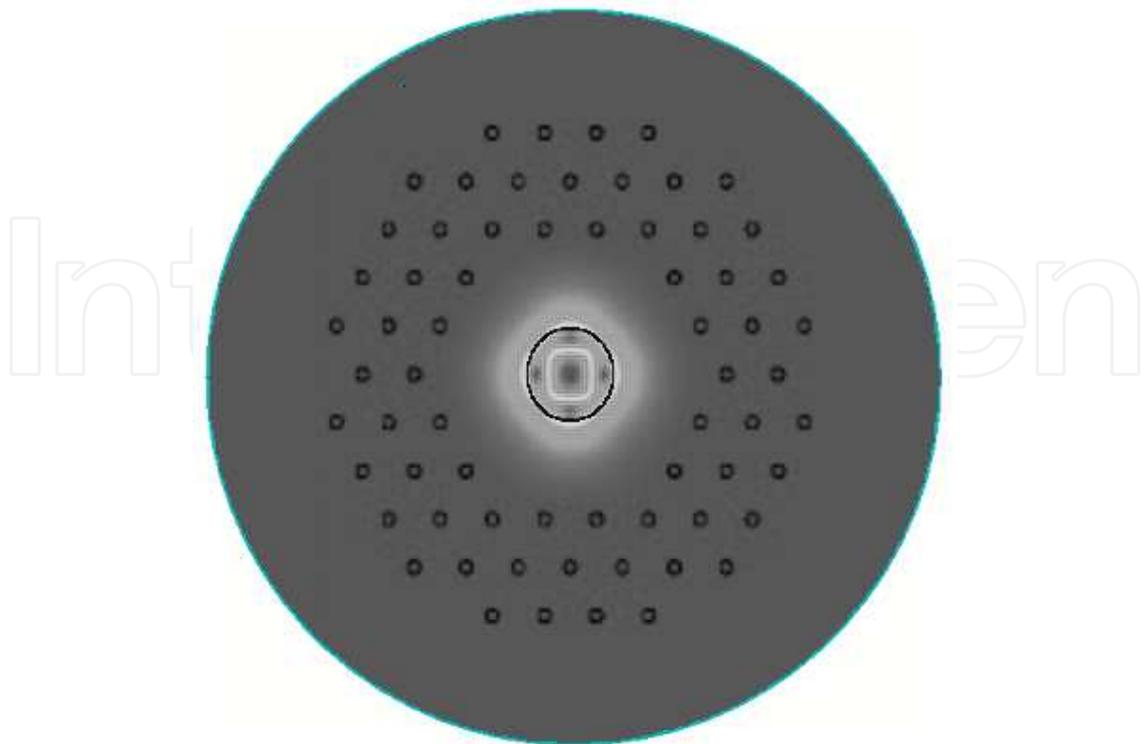


Figure 6. Wideband large mode area MOF with near zero flattened CD [3].

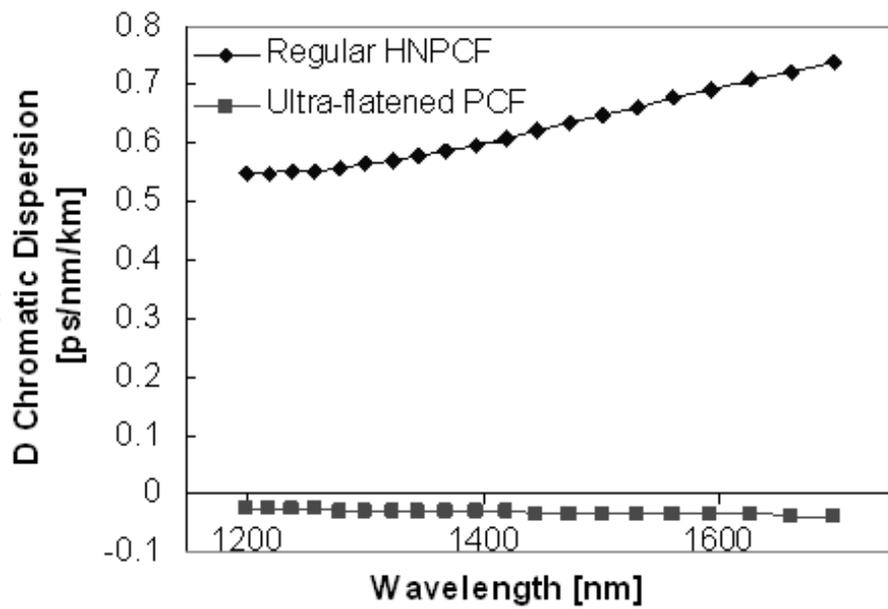


Figure 7. Dispersion in conventional microstructured fibre and proposed highly nonlinear MOF [3].

Wideband fibre could exhibit negative CD parameter, too. We propose a MOF for suppression in the band of 1.25-1.7 μm . We do not use any additives. Mode confinement is done by

optimizing the geometry of the core and the normalized hole diameter d/Λ , the accepted view is that the core size should be small. In the 1st ring, there is $d_1/\Lambda=0.9$. The proposal could be found in Figure 8. Doping the core could additionally improve CD properties, but it would surely worsen attenuation. One should pay attention to the fact that optimization of CD shall be done in the context of attenuation properties. Optimizing one parameter and ignoring another is unacceptable in high-speed transmission system fibres [1].

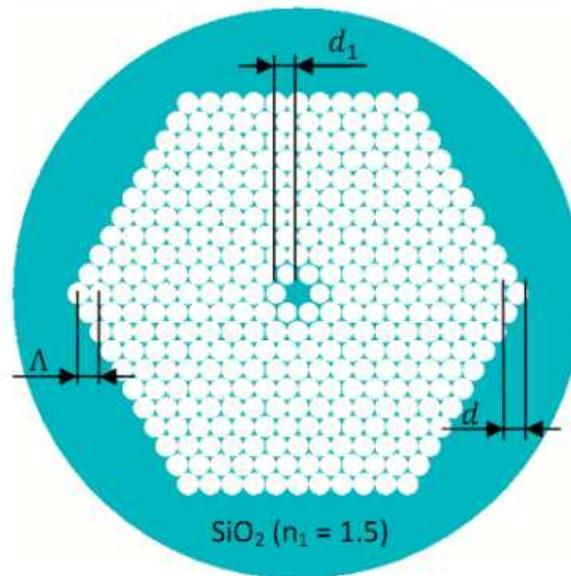


Figure 8. Cross section of designed microstructured fibre for wideband suppression of CD [1].

Having larger holes in the 1st ring, d_1 , is responsible for lower CD. On the contrary, by making smaller all the other holes (d) results in increasing dispersion. In Table 5, optimized structure is shown and its cross section is in Figure 9 [1].

Quantity [unit]	Value	Value	Value	Value	Value
CD [ps/nm/km]	-1580	-2040	-2259	-2094	-1930
Core index [-]	1.50	1.50	1.50	1.50	1.50
Theoretical losses [dB/cm]	$9.1 \cdot 10^{-6}$	$1.9 \cdot 10^{-3}$	$4.8 \cdot 10^{-2}$	$7 \cdot 10^{-2}$	$1.5 \cdot 10^1$
FWHM [nm]	Flat CD over 1.25-1.7 μm				
Lattice pitch [μm]	0.70	0.65	0.62	0.6	0.55
Hole diameter in 1 st ring d_1 [μm]	0.70	0.65	0.62	0.6	0.55
Hole diameter d [μm]	0.70	0.65	0.62	0.6	0.55
Number of rings [-]	10	10	10	10	10

Table 5. Specification of parameters for wideband CD suppressing MOF [1].

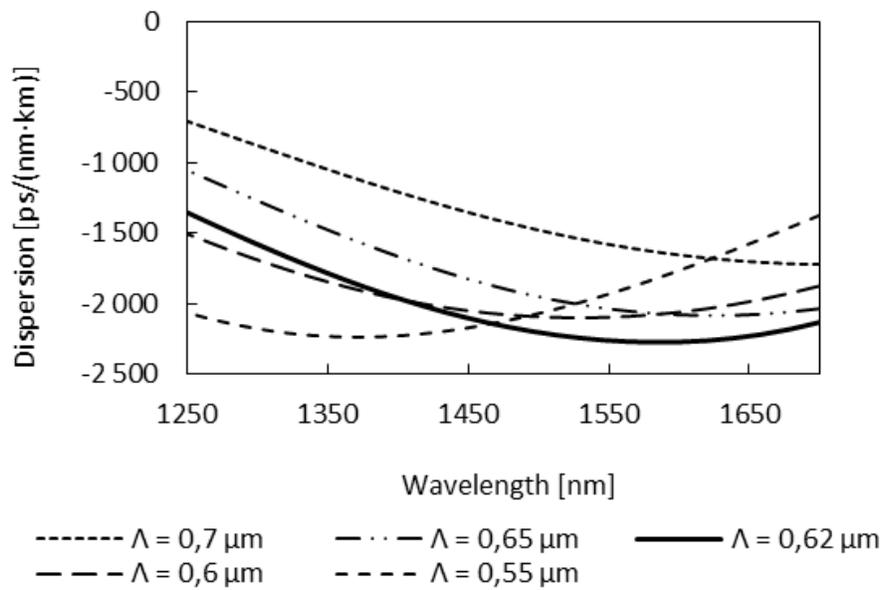


Figure 9. Resultant flattened negative value of CD over broad band of λ s 1.25-1.7 μm (lattice pitch is a parameter) [1].

Concerning the values of CD, the best design is the one for $\Lambda=0.62 \mu\text{m}$, for which CD is -2259 ps/nm/km , obtained at $1.55 \mu\text{m}$. Theoretical losses are 4.8 dB/cm . The optimized fibre is the one with $\Lambda=0.70 \mu\text{m}$, where CD parameter is -1580 ps/nm/km at $1.55 \mu\text{m}$. Theoretical loss is lowered to $9.1 \cdot 10^{-6} \text{ dB/cm}$. In this case it is possible to compensate dispersion of about 90 km of standard SMF.

5.4. Fluoride doped dispersion compensating fibres [32]

The considered fibre is a MOF employing the idea of a W-profile fibre with the core doped by using BaF_2 ($n_{\text{BaF}_2} = 1.468$ to raise its refractive index) and containing three holes in the 1st ring doped by using CaF_2 , $n_{\text{CaF}_2} = 1.426$ to reduce effective cladding index. Increased index contrast is responsible for enhanced CD, as in eq. (12). As for example, models optical glasses could be expressed using coefficients shown in Table 6.

Material	B_1	C_2	B_3	C_4	B_5	C_6
Silica	0.6961663	0.0684043	0.4079426	0.11624	0.897479	9.89616
BaF_2	0.6433560	0.0577890	0.5067620	0.109680	3.82610	46.3864
CaF_2	0.5675888	0.0502636	0.4710914	0.10039	3.848472	34.6490

Table 6. Sellmeier coefficients for the fluoride additives used in investigated MOF [32].

The structural and material properties are in Table 7. Large radius of CaF_2 holes and the low core size are necessary for flat CD (Figure 10). CD is $-413 \sim -415 \text{ ps/nm/km}$ at $1.4 - 1.65 \mu\text{m}$. Theoretical loss is $1.75 \cdot 10^{-4} \text{ dB/cm}$. CaF_2 doped holes affect the CD (Figure 11). The larger are the doped holes, the lower is resultant CD [32].

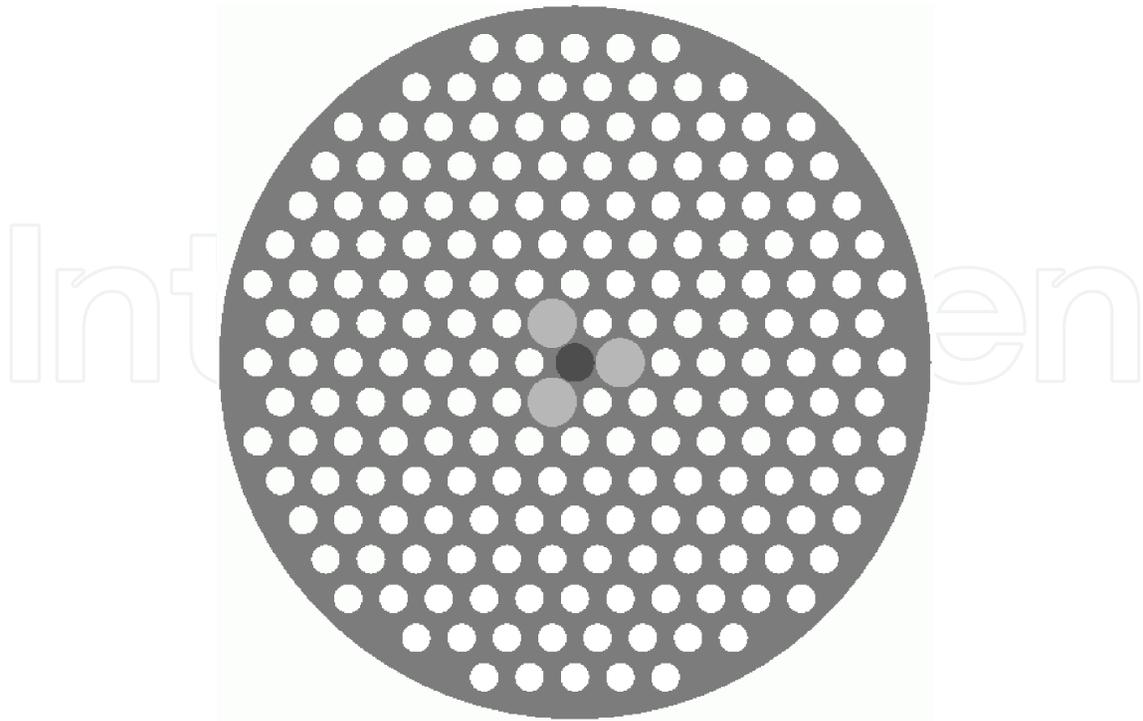


Figure 10. Fluoride-doped W-profile fibre’s cross section for infrared and telecom band [32].

Proposed fibre:	
Air hole diameter d [μm]	0.4
Lattice pitch Λ [μm]	0.7
Core size [μm]	1.3
Doped hole diameter d_1 [μm]	0.76
Core dopant material	BaF_2 $n = 1.468$ at $1.55 \mu\text{m}$
1 st ring doping material	CaF_2 $n = 1.426$ at $1.55 \mu\text{m}$
Normalized air-hole diameter d/Λ [-]	0.57

Table 7. Design specification of investigated W-profile MOF with doped holes in the 1st ring [32]

The air holes influence the dispersion slope. Larger d/Λ would limit the confinement losses. An interesting feature is that we use fluorides, ZBGA or ZBLAN, not just to dope the cladding, but we propose to use it as a background material instead of silicon dioxide (Figure 12). As a result, optimization of CD is more flexible. Last but not least, temperature and mechanical properties of such a fibre wouldn’t be worse [32].

Right combination and the composition of additives is responsible for optimized properties of a compound. Let us consider zirconium (Zr), barium (Ba), gadolinium (Gd) or aluminium (Al) that are the compounds of ZBGA material: $\text{ZrF}_4 - \text{BaF}_2 - \text{GdF}_3 - \text{AlF}_3$ [32]. The n_{eff} of ZBGA material could be represented by modified Sellmeier equation (17) [46], using the coefficients in Table 8 [45].

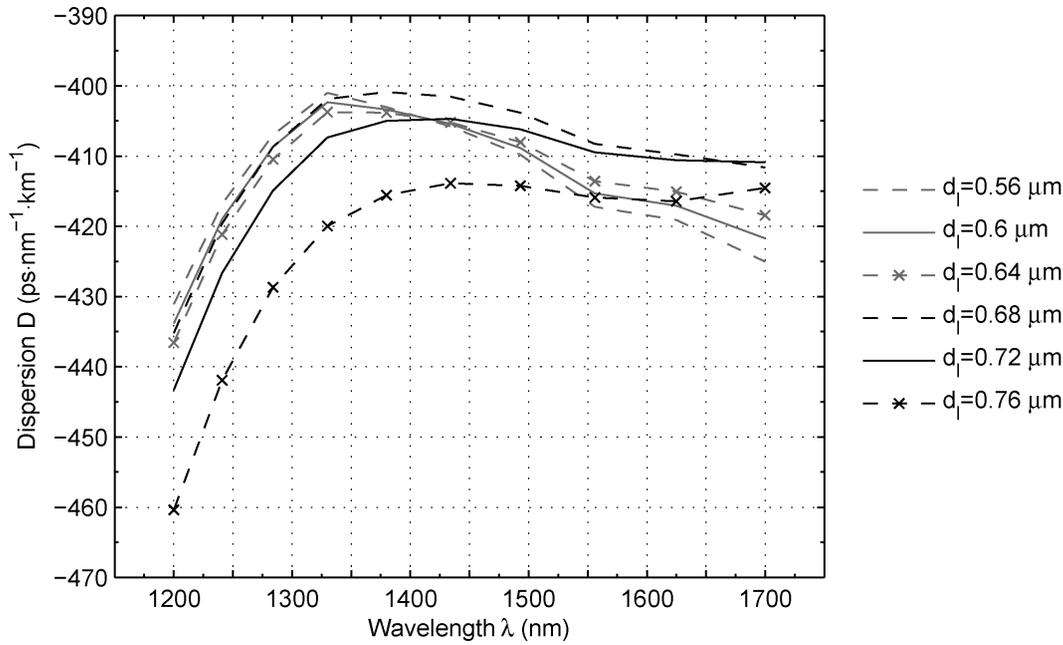


Figure 11. Wavelength evolution of CD with hole diameter of CaF₂ as a parameter [32].

$$n(\lambda) = \frac{A}{\lambda^4} + \frac{B}{\lambda^2} + C + D\lambda^2 + E\lambda^4 \tag{17}$$

Material	A	B	C	D	E
ZBGA at 25°C	2.98316e-6	3.39740e-3	6.81447e-3	-1.20276e-3	-5.48085e-6

Table 8. Sellmeier coefficients for the fluoride-background ZBGA fibre [45].

ZBGA has larger n_{eff} comparing with silicon dioxide. Tailored CD is expected [32].

Parametric sweep performed for the hole diameter showed that flatten CD is possible, which is shown in Figure 6. For hole diameter being equal to 0.44 μm, the evolution of CD is similar to one obtained for silicon dioxide. Larger n_{eff} of the ZBGA fibre requires larger radius of air-holes in the cladding to tailor CD [32].

BaF₂ could be used in the core and CaF₂ in the 1st ring, ZBGA as a background material (Figure 13). CD parameter is then possible within the range of -435 ~ -438 ps/nm/km and over the entire telecommunication band. At the same time, attenuation properties are not worse than those obtainable in fibres with silica as a background material [32].

5.5. Submicron dispersion compensating fibres with modified geometry [2]

One of the trends is to use a lattice with the pitch being less than one micrometre (so-called submicron lattice). Then, by careful adjustments of the diameter of holes (d_1 - d_3 in Figure 14),

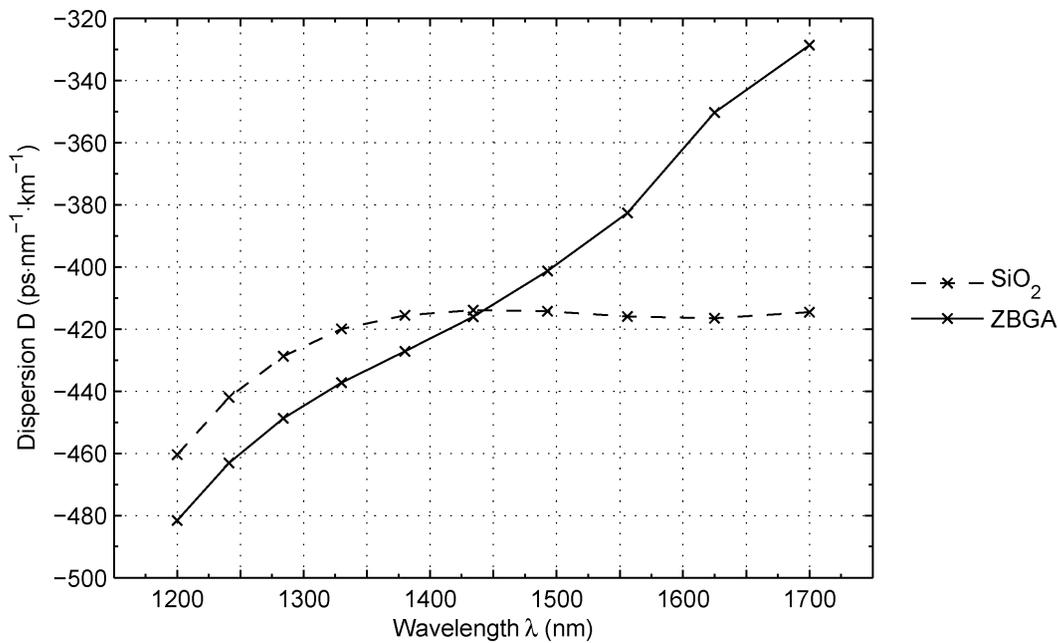


Figure 12. CD in SiO₂ and ZBGA used as a background material [32].

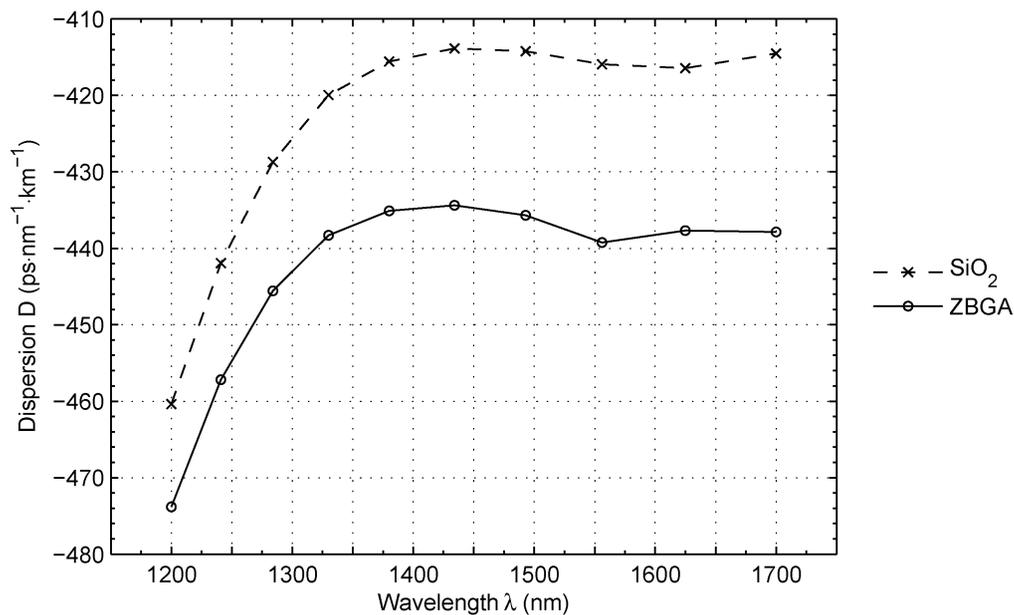


Figure 13. Proposed MOF with ZBGA material used as a background compared to a fibre with SiO₂ as a background [32].

where d_1 is hole diameter in the 1st ring of holes, one could obtain nearly zero CD for the λ s from the window 1.25-1.7 μm . Hole diameter and lattice pitch are submicron. Then, high confinement of light waves and strong waveguide dispersion is possible. The geometrical parameters of the fibre are in Table 9 and in Figure 14 [2]. CD and loss are simulated for the 1st light mode. Confinement losses are $6 \cdot 10^{-6}$ dB/km (Figure 15). Wavelength evolution of CD is shown in Figure 15 [2].

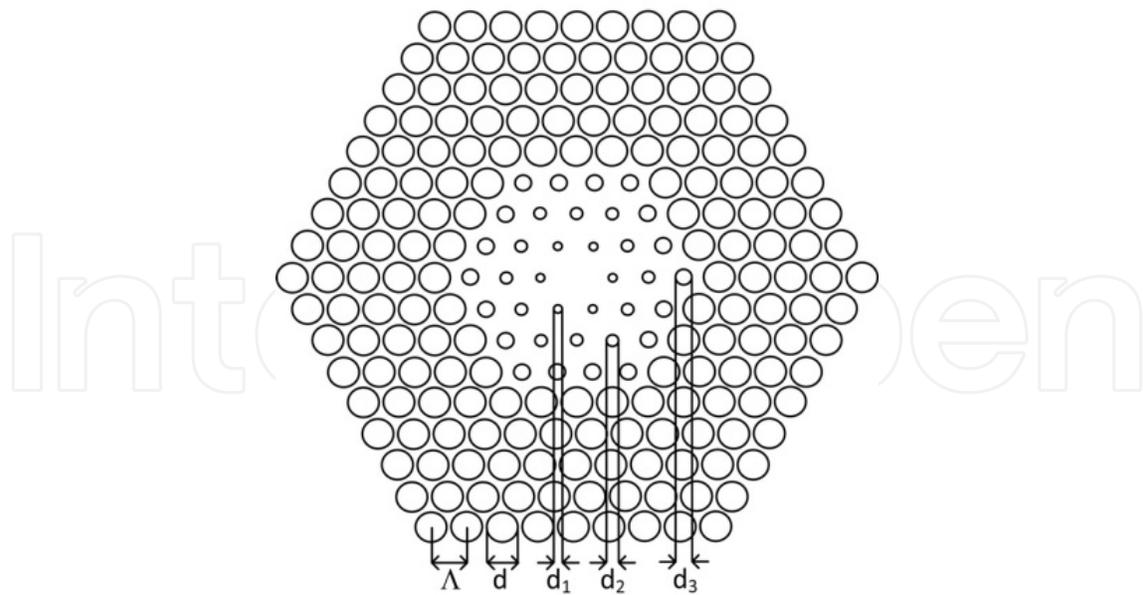


Figure 14. Cross section of a near zero CD flattened MOF with modified rings [2].

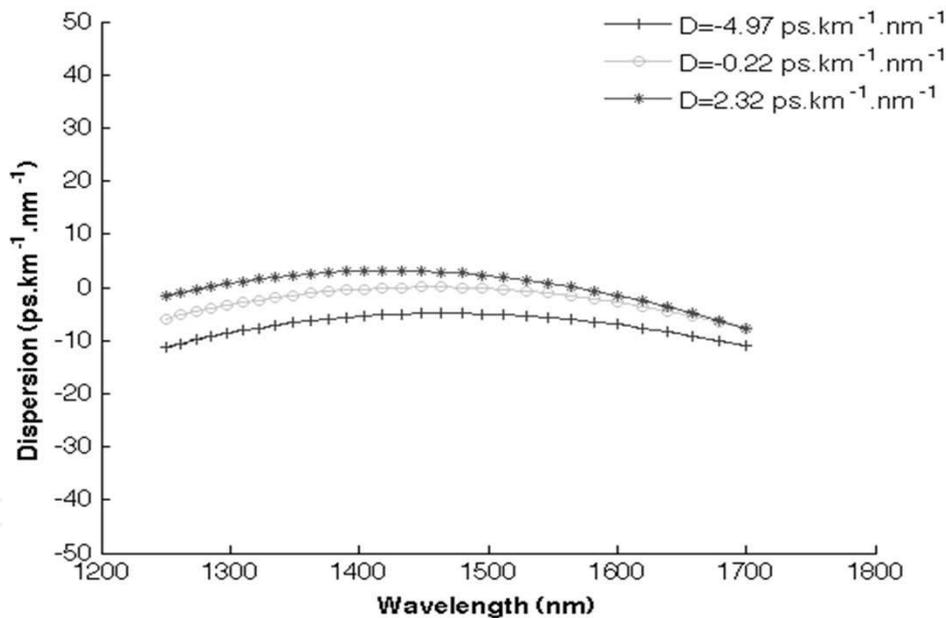


Figure 15. Near zero flattened CD for wideband utilization in telecommunications [2].

Obtained CD parameter is from -7.7 ps/nm/km to 3.1 ps/nm/km at the band of $(1.25, 1.7 \mu\text{m})$ and its average value is around 0.51 ps/nm/km. In the C-band, it is 1.35 ± 0.46 ps/nm/km. For both C and L bands CD is 0.12 ± 1.32 ps/nm/km [2]. Results for parametric iterations for air fraction changed in three most internal rings are shown in Figures 15 and 16. From the results summarized in Table 10 it could be concluded that the fibre has CD slope of -0.09 ps.nm².km⁻¹ is obtained for little variation of d_1 from other holes and is suited to the slope of conventional ITU-T G.657 fibres. The slope is less than 0.09 ps.nm².km⁻¹ [2].

d_1	d_2	d_3	$d = \text{const.}$	$\Lambda = \text{const.}$	CD at 1.55 μm
μm	μm	μm	μm	μm	ps/nm/km
0.134	0.305	0.318	0.355	0.8	2.32
0.134	0.298	0.325	0.355	0.8	-0.22
0.134	0.290	0.325	0.355	0.8	-4.97

Table 9. Geometrical parameters of a fibre with nearly zero flattened CD [2].

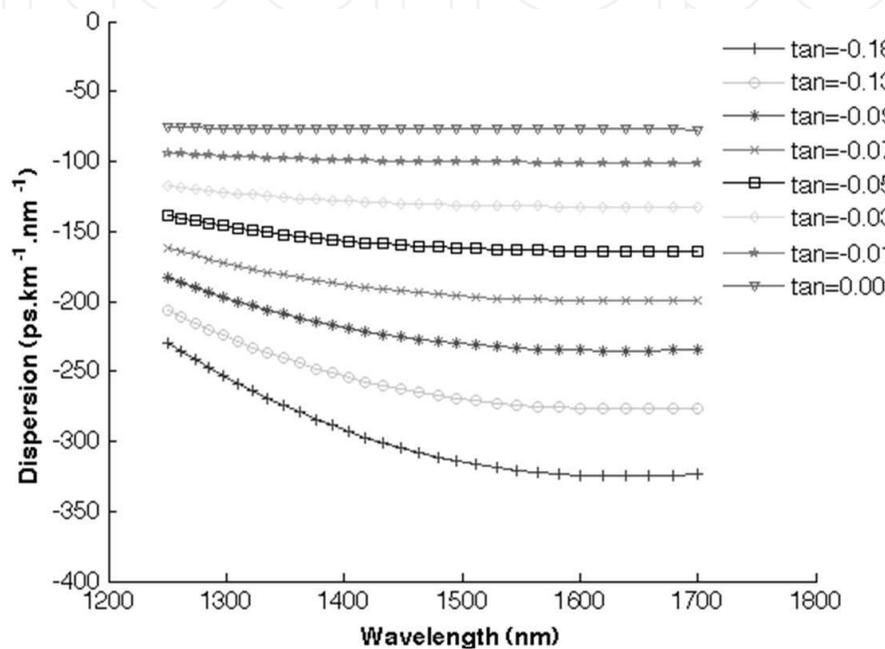


Figure 16. Optimized CD slope by varying the hole diameter in the 1st ring [2].

	d_1	$d_2, \text{ constant}$	$d_3, \text{ constant}$	$d, \text{ constant}$	CD slope
	μm	μm	μm	μm	ps.nm ⁻² .km ⁻¹
hole diameter of the 1 st ring	0.18	0.31	0.355	0.355	0.01
	0.20	0.31	0.355	0.355	-0.03
	0.22	0.31	0.355	0.355	-0.07
	0.24	0.31	0.355	0.355	-0.13
	0.25	0.31	0.355	0.355	-0.18

Table 10. Optimized dispersion slope by varying diameter of holes in the 1st ring [2].

Larger CD slope is here obtained by adjusting the value of d_3 (see Table 11, Fig. 16). At d_1 being fixed, linear wavelength evolution of CD is possible. It becomes nonlinear when the slope exceeds $-1 \text{ ps.nm}^{-2}.\text{km}^{-1}$. The obtained property could be applied in CD suppression performed on a fibre with the slope of $0.5 \text{ ps.nm}^{-2}.\text{km}^{-1}$ [2].

	$d_1 = \text{const.}$	$d_2 = d, \text{ constant}$	d_3	$d, \text{ constant}$	CD slope
	μm	μm	μm	μm	$\text{ps.nm}^{-2}.\text{km}^{-1}$
hole diameter of the 3 rd ring	0.265	0.355	0.35	0.355	-0.39
	0.265	0.355	0.27	0.355	-0.63
	0.265	0.355	0.23	0.355	-0.85
	0.265	0.355	0.17	0.355	-1.32

Table 11. Large CD slope obtained by tuning the hole size in the 3rd ring [2].

6. Final conclusions

We described optical fibres from the perspective of their CD properties, which has to be solved in telecommunication. The mechanisms governing CD properties in telecom fibres are shown. The considered fibres are suitable for potential suppression of group velocity dispersion, utilized mainly in the C-band (dual core fibres with high negative CD parameter) and in wideband applications (CD flattened MOFs and exact slope suppression fibres).

A special family of fibres is so-called fluoride fibres that have CD optimized through material dispersion. This idea is combined with the proposal of a W-type fibre, where particular regions are doped by using different additives, including fluorides, among others. ZBLAN material offers broader range with low attenuation (telecom and infrared range). It makes them very attractive for getting eventually applied in spectrometry or in applications in fibre-optic sensors.

The use of fluorides assessed their flexibility in CD optimization and potential use in wideband CD suppression. Last but not least, it has been shown that optimization of fibre's CD slope is possible in submicron lattice pitch without additives, potentially for exact slope suppression of standard International Telecommunication Union fibres.

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