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Fiber designs for high figure of merit and high slope dispersion compensating fibers

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Abstract. When the first dispersion compensating fiber modules were introduced to the market in the mid '90s, the only requirement to the fiber was that it should have a negative dispersion. As the bit rate and the complexity of the optical communication systems have increased, several other requirements have been added such as low loss, low non-linearities and the ability of broadband dispersion compensation.

1. Introduction

When the first dispersion compensating fiber modules were introduced to the market in the mid '90s, the only requirement to the fiber was that it should have a negative dispersion. As the bit rate and the complexity of the optical communication systems have increased, several other requirements have been added such as low loss, low non-linearities and the ability of broadband dispersion compensation.

Especially the demand of dispersion compensating fiber modules for broadband dispersion compensation has driven the development of new dispersion compensating fibers, so now, even with more than 100 000 dispersion compensating fiber modules deployed in systems worldwide, improvements to dispersion compensating fiber modules are constantly being introduced.

As the systems continuously become more advanced, so does the dispersion compensating fiber module. In this paper the process of designing the advanced dispersion compensating fibers will be discussed. One of the challenges of designing dispersion compensating fibers is to meet the expectations of both end users and the manufacturer of the fiber.

The end users' expectation to the optical properties of the dispersion compensating fiber module is that it can deliver broadband dispersion compensation with low added

Fig. 1. Two dispersion compensating fiber modules. The module in back is a conventional dispersion compensating fiber module while the module in front is the dispersion compensating fiber module with reduced physical dimensions described in section 6.

loss and non-linearities to the system. Furthermore, the optical properties have to be stable in changing operating conditions with respect to temperature and humidity. As to the physical appearance of the module, the dispersion compensating fiber module normally consists of the dispersion compensating fiber wound onto a metallic spool with connectors spliced to each end of the fiber as shown in Fig. 1. These spools are placed in metal boxes designed to meet the space requirements of the end user. As will be discussed later in this paper, dispersion compensating fiber modules with reduced physical dimensions are currently being developed.

Beside the demands of the end users, the manufacturer of the dispersion compensating fibers also has some demands to the design of the dispersion compensating fiber. The most important issue here is how much the optical properties of the dispersion compensating fibers change with the small variations in the index profile of the fiber, which are unavoidable during the manufacturing process.

This paper will focus on some of the trade offs encountered during the process of designing and manufacturing dispersion compensating fibers. Three special cases will be considered: Dispersion compensating fibers with a high figure of merit, dispersion

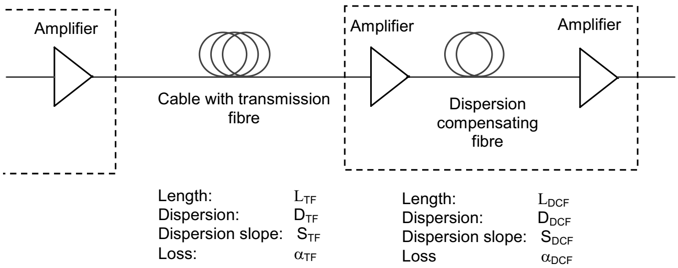

Fig. 2. Link consisting of cabled transmission fiber and amplifier with dispersion compensating fiber.

compensating fibers with a high dispersion slope and dispersion compensating fiber modules with reduced physical dimensions.

All three types of fiber represent a challenge with respect to fiber design as they either have extreme dispersion properties or bend loss properties. As will be discussed in this paper, several trade offs exist between the desired dispersion properties and properties such as bend losses and manufacturability.

First some basic requirements for dispersion compensation will be mentioned. Next, some of the basic considerations for designing dispersion compensating fibers will be discussed followed by a discussion of the major contributions to the attenuation of dispersion compensating fibers.

This leads to the discussion of the design of the three types of dispersion compensating fibers: the dispersion compensating fiber with a high figure of merit, the dispersion compensating fiber with a high dispersion slope and finally the dispersion compensating fiber with reduced physical dimensions.

At last the nonlinear impairments on the system from the dispersion compensating modules will be discussed, with a comparison of dispersion compensating modules with either a high figure of merit or a high dispersion slope.

2. Dispersion Compensation

Although dispersion compensating fibers can be cabled and used as a part of the transmission span, the common use of them is to place them as modules in the amplifier between two amplification stages as shown in Fig. 2.

Whether the dispersion of the transmission fiber should be fully compensated, or whether a slight over or under compensation is advantageous from a system point of view will not be considered here. For the rest of this paper, it will be assumed that the dispersion of the transmission fiber should be fully compensated.

The performance of a dispersion compensating fiber module over a wide wavelength range can be evaluated using the residual dispersion, which is the dispersion measured after the dispersion compensating fiber module in the receiver. The residual dispersion variation is the largest variation of the residual dispersion in the wavelength

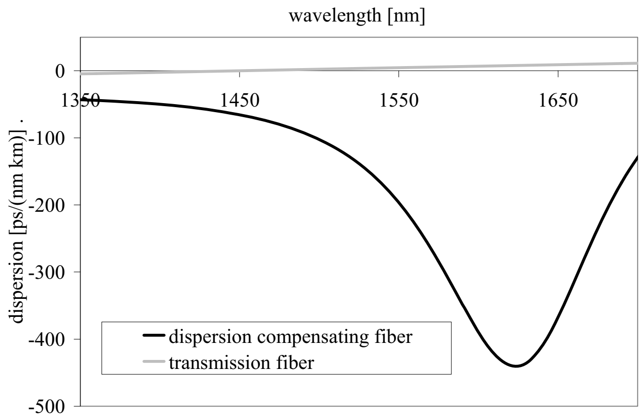

Fig. 3. Dispersion of transmission fiber and of dispersion compensating fiber. The dispersion slope of the transmission fiber is almost constant (dispersion curvature close to zero) for the entire wavelength range while the dispersion slope for the dispersion compensating fiber changes significantly making perfect dispersion match over a broad wavelength range impossible.

range considered. It has been shown that the theoretical tolerance on the residual dispersion variation for a non return to zero (NRZ) signal assuming a 1-dB eye-closure penalty is around 60 ps/nm at 40 Gb/s. [2]

The total residual dispersion D_{res} of the link shown in Fig. 2 is given by

$$D_{\mathrm{res}} = D_{\mathrm{TF}} L_{\mathrm{TF}} + D_{\mathrm{DCF}} L_{\mathrm{DCF}}. \tag{1}$$

The dispersion of any fiber or combination of fibers can be modeled by a Taylor expansion around the center wavelength as

$$D_(\lambda) = D(\lambda_0) + D'(\lambda_0)(\lambda-\lambda_0) + \frac{1}{2}D''(\lambda_0)(\lambda-\lambda_0)^2 + \frac{1}{6}D'''(\lambda_0)(\lambda-\lambda_0)^3 \ldots . \tag{2}$$

with D' being the first derivative of the dispersion (the dispersion slope, S), D'' the second derivative (the dispersion curvature C) and D''' the third derivative of the dispersion.

The dispersion of most transmission fibers is well described by including only the first two terms, the dispersion and the dispersion slope, in Eq. (2). Consequently, the dispersion of the perfect dispersion compensating fiber should have a slope matching that of the transmission fiber while all higher order dispersion terms in Eq. (2) should be small. The dispersion of a transmission fiber and a dispersion compensating fiber are shown in Fig. 3. Higher order terms are by no means negligible for the dispersion of dispersion compensating fiber and several higher order terms must be included in the description of the residual dispersion of the system in Fig. 2.

If zero dispersion is desired after the dispersion compensating fiber module in the receiver, the length of the dispersion compensating fiber (L_{DCF}) is given as

$$L_{\mathrm{DCF}} = -\frac{D_{\mathrm{TF}}}{D_{\mathrm{DCF}}} L_{\mathrm{TF}}. \tag{3}$$

In order to compensate the dispersion over a large wavelength range, the dispersion slope must be compensated as well. The residual dispersion slope is expressed as

$$S_{\mathrm{res}} = S_{\mathrm{TF}} L_{\mathrm{TF}} + S_{\mathrm{DCF}} L_{\mathrm{DCF}}. \tag{4}$$

If Eq. (3) is inserted in Eq. (4), the condition for simultaneous dispersion and dispersion slope compensation is expressed as

$$\frac{S_{\mathrm{DCF}}}{D_{\mathrm{DCF}}} = \frac{S_{\mathrm{TF}}}{D_{\mathrm{TF}}}. \tag{5}$$

The ratio of dispersion slope to dispersion is defined as the relative dispersion slope (RDS) [3]:

$$\mathrm{RDS} = \frac{S}{D}. \tag{6}$$

It has often been stated that in order to achieve perfect dispersion compensation, the slope of the dispersion compensating fiber must match that of the transmission fiber. [4]

This is the case when the ratio of dispersion slope to dispersion [the relative dispersion slope (RDS)], is the same for the two fibers.

That perfect dispersion compensation would be obtained by matching the slopes of the two fibers would only be true if higher order terms from Eq. (2) such as the curvature were not needed to describe the dispersion of the dispersion compensating fiber. It is only true that slope match gives the lowest possible residual dispersion when the dispersion curvature is not considered.

The relative dispersion curvature (RDC), which is defined as

$$\mathrm{RDC} = \frac{C}{D} \tag{7}$$

can be used for calculating the total curvature of a link consisting of N fibers

$$C_{\mathrm{tot}} = \frac{1}{L} \sum_{i=1}^{i=N} \mathrm{RDC}_i D_{\mathrm{tot},i} \tag{8}$$

with RDC_i being the relative dispersion curvature of fiber i, $D_{\mathrm{tot},i}$ the total dispersion of fiber i and L the length of the link. This expression is useful if the dispersion curvature of a link consisting of fibers with high dispersion curvatures is to be minimized. [5]

As mentioned previously, since the dispersion of the transmission fiber is well described by the first two terms in Eq. (2), all higher order terms, and thereby the curvature—and relative dispersion curvature for the dispersion compensating fiber should be as small as possible in order to obtain a low total dispersion curvature and thereby a low residual dispersion.

Figure 4 shows the residual dispersion of 4 links of the same type as shown in Fig. 2. The transmission fiber is a TrueWave® RS (Table 1) and the four different dispersion compensating fibers are all realized fibers.

The residual dispersion of the link is calculated from the measured dispersions of the transmission and dispersion compensating fibers.

The residual dispersion variation is one way to measure the quality of the dispersion compensation. Another is usable bandwidth, which can be defined as the bandwidth

Table 1. Dispersion, dispersion slope and relative dispersion slope (RDS) of transmission fibers at 1550 nm.

	Dispersion [ps/nm·km]	Dispersion slope [ps/nm^{2}km]	RDS [nm^{-1}]
Standard single-mode optical fiber (SSMF)			
ITU: G.652	16.5	0.058	0.0036
Non-zero dispersion-shifted single-mode optical fiber (NZDF): ITU: G.655			
TrueWave® REACH fiber	7.1	0.042	0.0058
TeraLight* fiber	8	0.058	0.0073
TrueWave® RS fiber	4.5	0.045	0.010
ELEAF* fiber	4.2	0.085	0.02
Dispersion shifted single-mode optical fiber (DSF)			
(at 1590 nm) ITU:G.653	2.8	0.07	0.025

*TeraLight is a registered trademark of Alcatel; LEAF is a registered trademark of Corning.

for which the residual dispersion variation is below a given value. [6] In Fig. 4 the usable bandwidth is shown as the bandwidth where the residual dispersion variation is within 0.2 ps/(nm km) corresponding to a theoretical transmission length of 300 km of a NRZ signal at 40 Gb/s assuming the transmission length to be limited by the dispersion only. [2]

In Fig. 4(a) the RDS of the transmission fiber is different from the RDS of the dispersion compensating fiber and the usable bandwidth is limited to 12 nm by the slope mismatch.

In Fig. 4(b) the dispersion slopes of the two fibers are matched resulting in a usable bandwidth that is only limited by the dispersion curvature of the dispersion compensating fiber. By reducing the curvature of the dispersion compensating fiber and keeping the slopes matched, an improvement in usable bandwidth can be obtained as shown in Fig. 4(c), but the improvement is only from the usable bandwidth of 51 nm in Fig. 4(b) to the usable bandwidth of 57 nm in Fig. 4(c). The largest usable bandwidth can be obtained if the curvature of the dispersion compensating fiber is minimized while allowing a small slope mismatch as shown in Fig. 4(d). This figure shows the same dispersion compensating fiber as in Fig. 4(c) but the transmission fiber of Figure 4d has a slightly lower dispersion slope. This overcompensation of the dispersion slope results in a usable bandwidth of 82 nm and is an example of how slope match is not always desirable in order to obtain a large usable bandwidth.

Whether the slopes should be perfectly matched for dispersion compensating fibers with low curvature depends of course on the requirements to the residual dispersion. In Fig. 4(c), even though the usable bandwidth as defined above is smaller than in Fig. 4(d), the residual dispersion variation from 1550 to 1570 nm is less than 0.01 ps/(nm km) and for some applications a low residual dispersion is more important than a large usable bandwidth.

Typical dispersions and RDS values for a number of commonly used transmission fibers at 1550 nm are listed in Table 1.

Of the transmission fibers listed in Table 1, standard single mode fiber (SSMF) has the highest dispersion and thus the highest need for dispersion compensating. The ITU: G.655 Non Zero Dispersion-shifted single-mode optical Fibers (NZDF) of Table 1 were developed in order to reduce the need for dispersion compensation, but

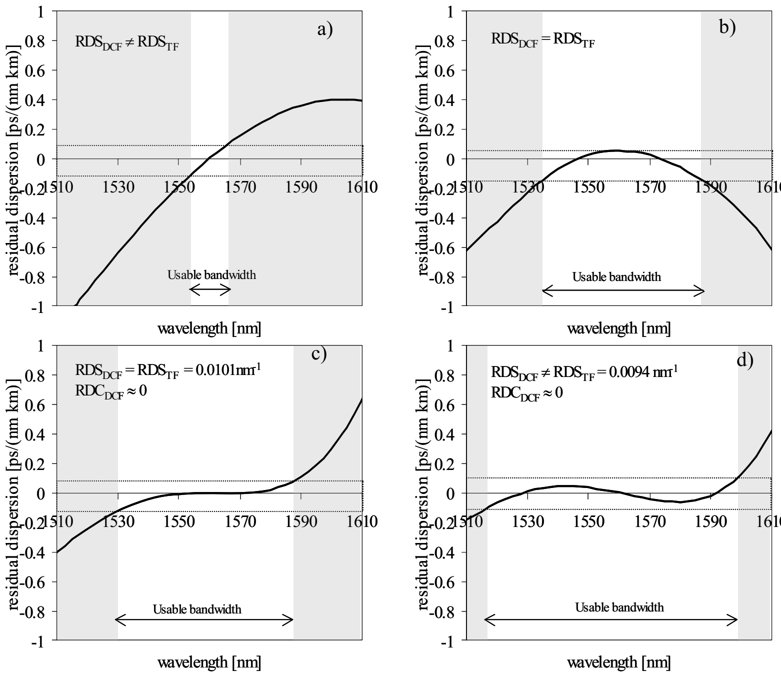

Fig. 4. Residual dispersion variation and usable bandwidth of 4 links consisting of a NZDF (TrueWave®RS) and a dispersion compensating fiber. The usable bandwidth is defined here as the bandwidth for which the residual dispersion is within 0.2 ps/(nm km). (a) RDS of the transmission fiber and the dispersion compensating fiber do not match. (b) RDS of the transmission fiber and the dispersion compensating fiber are matched. (c) RDS of the transmission fiber and the dispersion compensating fiber are matched. The curvature of the dispersion compensating fiber is low. (d) RDS of the transmission fiber is slightly lower than the RDS of the dispersion compensating fiber. The curvature of the dispersion compensating fiber is low.

as the bit rate of the systems increases, the control of the dispersion becomes more important and even the low dispersion of the NZDF requires compensation. Dispersion compensating fiber modules with slope match to all commonly installed transmission fibers are available.

The main challenge when designing dispersion compensating fibers for ITU: G.652 standard single mode fiber (SSMF) is to lower the attenuation of the dispersion compensating fiber module. During the past decade the attenuation of dispersion compensating fiber modules for 100 km SSMF have decreased from 9.5 to less than 5 dB but further improvement is still possible. Another challenge for dispersion compensating fiber modules for SSMF is to reduce the physical size of the dispersion compensating fiber module which will reduce the space requirements as well as the material costs.

For the non-zero dispersion fibers (NZDF) with low dispersion slope below 0.01 nm^{-1}, dispersion compensating fiber modules can easily be designed. The challenge for designing dispersion compensating fibers for NZDF lies with the high slope NZDF with RDS above 0.01 nm^{-1}.

In this paper some of the trade offs, which must be considered when designing dispersion compensating fibers will be discussed. Three cases will be discussed: Dispersion compensating fibers with high figure of merit (FOM) for SSMF, dispersion compensating fibers with high dispersion slope and dispersion compensating fibers for SSMF with reduced physical dimensions.

3. Designing Dispersion Compensating Fibers

The dispersion compensating fibers considered in this paper all have triple clad index profiles with a core surrounded by a region with depressed index (the trench) followed by a raised ring (Figure 5a). This type of fiber is sometimes described as a dual concentric core fiber. Other designs for dispersion compensating fibers have been reported such as a quintuple clad fiber [7] or W-shaped profiles. [8] However, as most of the achieved dispersion properties can be obtained with a triple clad index profile as well, [9] only this type of profiles will be discussed here.

The dispersion is related to the second derivative of the propagation constant (β) by

$$D = \frac{-2\pi c}{\lambda^2}\frac{d^2\beta}{d\omega^2}. \tag{9}$$

The second derivative of the propagation constant is given by

$$\frac{d^2\beta}{d\omega^2} = \frac{1}{c}\left(2\frac{dn_e}{d\omega} + \omega\frac{d^2n_e}{d\omega^2}\right) \tag{10}$$

with ω being the frequency and n_e the effective index.

The propagation constant can be written in terms of the free space wave number and the effective index:

$$\beta = k_0 n_e \tag{11}$$

with the free-space wave number k_0 defined as

$$k_0 = \frac{\omega}{c} = \frac{2\pi}{\lambda} \tag{12}$$

and the effective index as

$$n_e = \Delta n_e + n_0 \tag{13}$$

with Δn_e being the effective index difference and n_0 the refractive index of the cladding the dispersion can be written as

$$D = \frac{-2\pi c}{\lambda^2}\frac{d^2 k_0 \Delta n_e}{d\omega^2} + \frac{-2\pi c}{\lambda^2}\frac{d^2 k_0 n_0}{d\omega^2} = D_{\mathrm{waveguide}} + D_{\mathrm{material}} \tag{14}$$

with the first term giving the waveguide dispersion and the second term giving the material (or cladding) dispersion.

The propagation properties in a fiber with a triple clad index profile can be understood by considering the two guiding regions, the core and the ring regions separately. In Figs. 5(b) and (c) the two guiding regions are shown. The core index profile has

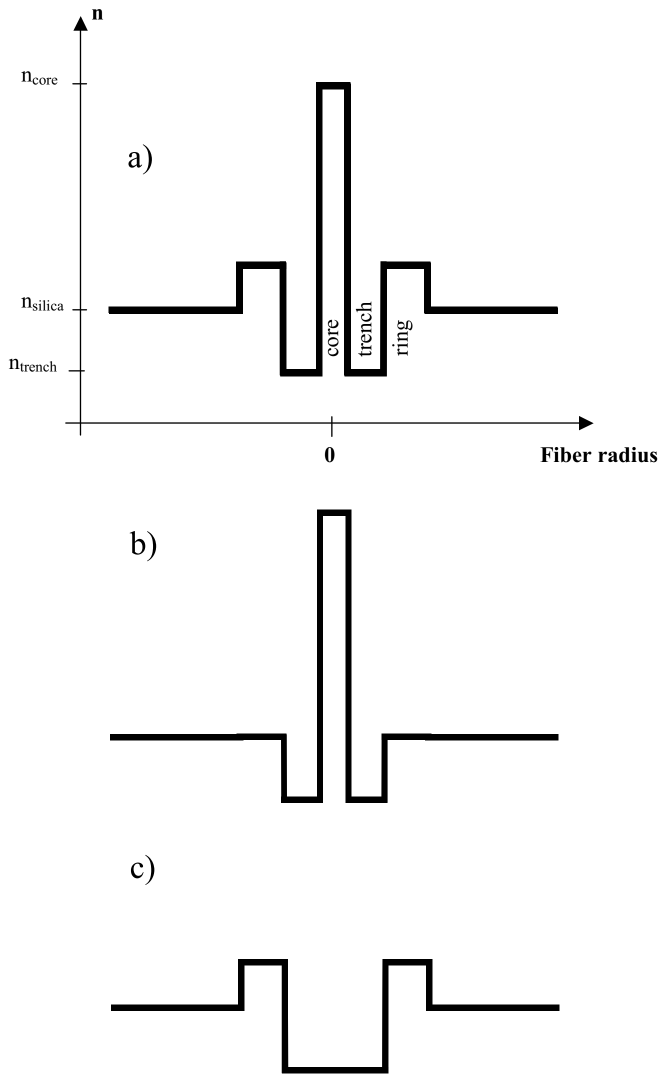

Fig. 5. Triple clad index profile. (a) The core is surrounded by the deeply down-doped trench followed by a raised ring. The core and ring are doped with germanium in order to increase the refractive index with respect to silica while the trench is doped with fluorine to lower the refractive index. (b) The index profile for the core guide. (c) The index profile for the ring guide.

been obtained by removing the ring from the triple clad index profile while the ring profile has been obtained by removing the core from the triple clad index profile.

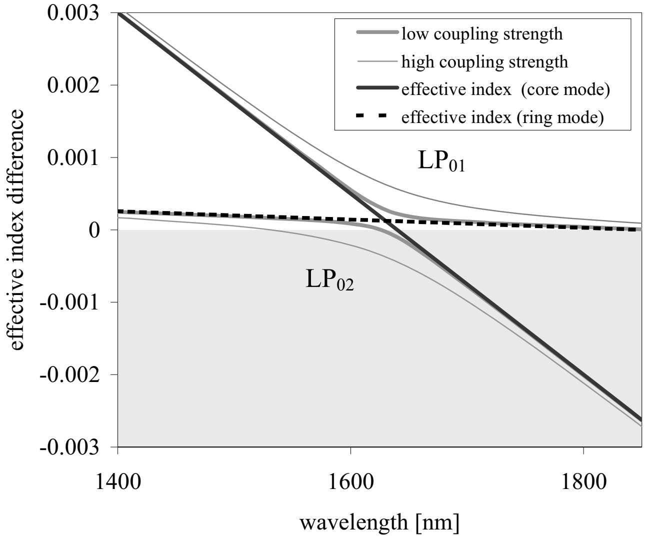

Fig. 6. Effective index differences for core-, ring-, LP_{01} and LP_{02} modes. The LP_{01} and LP_{02} modes are shown for high and low coupling strengths between the core and ring modes. A high coupling strength results in a low curvature at the cross over point while a low coupling strength results in a high curvature. The modes are not guided for $n_{\text{eff}} < 0$.

Using this supermode approach can be a powerful way to gain an intuitive understanding of how changes in the index profile changes the propagation properties of the fiber.

The effective index of the combined modes can be described by

$$n_e = \frac{n_{e(\text{core})} + n_{e(\text{ring})}}{2} \pm \sqrt{\kappa^2 + \left(\frac{(n_{e(\text{core})} - n_{e(\text{ring})})^2}{4}\right)} \tag{15}$$

with $n_{e(\text{core})}$ being the effective index of the core mode, $n_{e(\text{ring})}$ the effective index of the ring mode and κ the coupling strength between the two modes. [9]

The effective index n_e of the LP_{01} mode of the combined system is shown in Fig. 6 for both a low and a high coupling strength between the core and ring along with the effective index of the core and the ring mode. At short wavelengths the effective index of the LP_{01} mode approaches that of the core mode, indicating that the LP_{01} mode is confined mainly to the core. At longer wavelengths the effective index of the LP_{01} mode approaches that of the ring, indicating that the mode is confined to the ring.

The cross over-point is where the effective indices of the core and ring modes intersect. The coupling strength between the two modes determines the curvature of the effective index difference in the cross-over point and thus the dispersion of the LP_{01} (and LP_{02}) mode. With a low coupling strength, the interaction between the core and ring mode is small and the curvature of the effective index difference will be high while the opposite is the case for a high coupling strength.

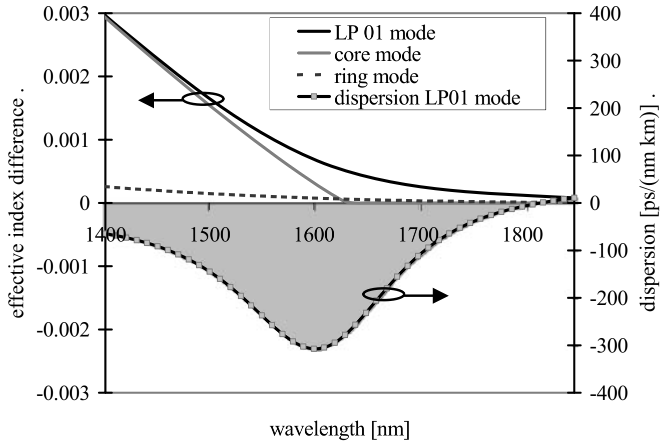

Fig. 7. The effective index difference of the ring, core and LP_{01} mode along with the resulting dispersion. Since the dispersion is the second derivative (curvature) of the effective index difference, the minimum of the dispersion curve is found at the wavelength for maximum curvature of the effective index.

As can be seen from Figure 7, the minimum of the dispersion of the LP_{01} mode occurs approximately were the curvature of the effective index difference reaches a maximum.

The first derivative of the propagation constant with respect to wavelength is the group delay. Consequently the area above the dispersion curve (shaded gray in Fig. 7) must be equal to the difference in group delay at the short and long wavelength side of the minimum of the dispersion curve. As the group delay of the LP_{01} mode approaches that of the core mode at short wavelengths and that of the ring mode at longer wavelengths, the area above the dispersion curve must be the same for different index profiles, unless the slope of the effective index difference of the core and ring modes changes significantly.

3.1. Scaling of the Triple Clad Index Profile

By changing the widths and indices of the triple clad index profile the dispersion curve given by Eq. (10) is changed. [10]

The scalar wave equation can be written as

$$\nabla^2_{r,\theta}\varphi + \frac{4\pi^2}{\lambda^2}2n_0\Delta n\varphi = \frac{4\pi^2}{\lambda^2}2n_0\Delta n_e\varphi \tag{16}$$

with $\nabla^2_{r,\theta}$ being the laplacian operator, Δn the refractive index difference, Δn_e the effective index difference and φ the scalar electric field. Terms in the order of Δn_e^2 and Δn^2 have been neglected.

If Eq. (16) is written for two different fiber profiles that are related to each other by

$$\Delta n^* = a\,\Delta n \tag{17}$$

and

$$r^* = b\,r \tag{18}$$

with * denoting the scaled profile, a being the index scale factor and b being the radius scale factor, Eq. (16) for the two index profiles will become the same if the effective index difference is scaled as

$$\Delta n_e^* = a\,\Delta n_e \tag{19}$$

and the wavelength is scaled as

$$\lambda^* = b\,\sqrt{a}\lambda. \tag{20}$$

Consequently the dispersion scales as

$$D^*_{\mathrm{waveguide}} = \frac{-2\pi c}{\lambda^*}\frac{d^2 k_0^* \Delta n_e^*}{d\omega^{*2}} = \frac{\sqrt{a}}{b}\frac{-2\pi c}{\lambda}\frac{d^2 k_0 \Delta n_e}{d\omega^2} = \frac{\sqrt{a}}{b} D_{\mathrm{waveguide}} \tag{21}$$

and the dispersion slope as

$$S^*_{\mathrm{waveguide}} = \frac{dD^*_{\mathrm{waveguide}}}{d\lambda^*} = \frac{d\left(\frac{\sqrt{a}}{b} D_{\mathrm{waveguide}}\right)}{d(b\sqrt{a}\lambda)} = \frac{1}{b^2} S_{\mathrm{waveguide}}. \tag{22}$$

If the radius scale factor b is related to the index scale factor a by

$$b = \frac{1}{\sqrt{a}}; \tag{23}$$

the relative dispersion slopes of the two fibers will be the same [Eqs. (6), (21) and (22)]:

$$\mathrm{RDS}^*_{\mathrm{waveguide}} = \mathrm{RDS}_{\mathrm{waveguide}}. \tag{24}$$

A consequence of this is that the effective index can be changed significantly without changing the waveguide dispersion.

The scaling only applies to the waveguide dispersion; consequently an error is introduced in the scaled dispersion due to the neglect of the material dispersion. But for most dispersion compensating fibers this error will be small since the material dispersion around 1550 nm is at the order of 20 ps/(nm km). An example is shown in Fig. 18 where a scaling of the radii of all layers of a triple clad index profile by a factor of 1.2 and a scaling of the indices by a factor of $1/\sqrt{1.2}$ results in an error of 3.7 ps/(nm km) on the dispersion of –158 ps/(nm km) of the scaled profile.

The scaling of the profile can be performed on the entire profile or on each of the guiding regions separately. So, by decreasing the core diameter, the wavelength where the effective index of the core and the ring mode intersects is decreased and thereby the wavelength of the minimum of the dispersion curve. The shift of the dispersion curve when the core width is changed can be used as a measure of how sensitive the design is to the small variations in core diameter, which are unavoidable during manufacturing.

By changing the width of the trench, the slope of the effective index difference for the core and ring modes remains largely unchanged. Consequently, the area under the dispersion curve is the same for fibers with different widths of the trench, but a significant change in the slope of the dispersion curve is seen. This will be treated further in section 5.

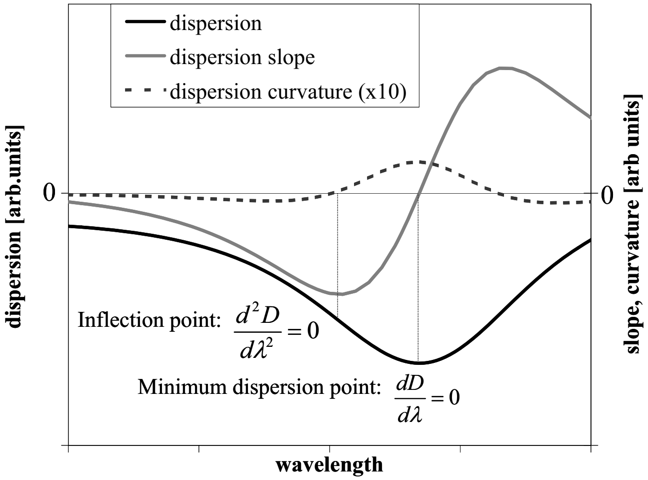

Fig. 8. Dispersion, dispersion slope and dispersion curvature for a dispersion compensating fiber. The dispersion curvature has been scaled with a factor of 10 in order to be plotted on the same axis as the dispersion slope. The minimum dispersion is found where $\frac{dD}{d\lambda} = 0$. The inflection point is where $\frac{d^2D}{d\lambda^2} = 0$. At wavelengths close to the inflection point, the dispersion curvature is low, resulting in a low residual dispersion. At wavelengths longer than the inflection point very negative dispersions can be obtained while at wavelengths shorter than the inflection point the maximum RDS can be found.

An important point on the dispersion curve is the inflection point (Fig. 8) where the second derivative of the dispersion, the curvature changes sign from negative to positive. The curvature around the inflection point is low and dispersion compensating fibers operating close to the inflection point can be used to obtain a very low residual dispersion as shown in Fig. 4(c)–(d). At wavelengths shorter than the inflection point the maximum value for RDS can be found while at wavelengths longer than the inflection point a very negative dispersion can be obtained. At the point of minimum dispersion, the curvature also reaches its maximum value; consequently the residual dispersion at this point will be high.

In the next sections some design strategies for dispersion compensating fibers with high negative dispersion, high dispersion slope and reduced physical dimensions will be discussed.

The properties of the fibers have been calculated solving the equation 16 using a finite elements formulation to obtain β and the fields of the guided modes.

Throughout this paper, simulated dispersion curves will be used to illustrate the design strategies for the various kinds of the dispersion compensating fibers.

4. Dispersion Compensating Fibers with a High Figure of Merit

While dispersion compensating fiber modules are necessary with respect to dispersion control, they decrease the performance of the system with respect to loss. The added loss from the dispersion compensating fiber module increases the need of amplification in the system thereby degrading the signal to noise ratio and adding cost.

The added loss from a dispersion compensating fiber module, $\alpha_{\mathrm{DCFmodule}}$ to a system can be expressed as

$$\alpha_{\mathrm{DCFmodule}} = L_{\mathrm{DCF}}\alpha_{\mathrm{DCF}} + \alpha_{\mathrm{splice}} + \alpha_{\mathrm{connector}} \tag{25}$$

with α_{DCF} being the attenuation coefficient of the dispersion compensating fiber (dB/km), L_{DCF} the length of dispersion compensating fiber in the module (km), α_{splice} the splice losses between the dispersion compensating fiber and the connectors and $\alpha_{\mathrm{connector}}$ the loss of the connector (dB).

As the length of dispersion compensating fiber can be expressed as

$$L_{\mathrm{DCF}} = D_{\mathrm{tot}}/D_{\mathrm{DCF}}$$

with D_{tot} being the accumulated dispersion on the transmission fiber, the length of dispersion compensating fiber in the module can be decreased by increasing the negative dispersion coefficient (D_{DCF}) on the dispersion compensating fiber.

This leads to a figure of merit for dispersion compensating fibers defined as

$$\mathrm{FOM} = \frac{-D_{\mathrm{DCF}}}{\alpha_{\mathrm{DCF}}}. \tag{26}$$

A high figure of merit signifies that the dispersion compensating fiber module adds less loss to the system.

Since the accumulated dispersion on NZDF is lower than on SSMF a high figure of merit is particularly interesting for a dispersion compensating fiber with slope match to SSMF than for one with slope match to NZDF. 100 km SSMF will accumulate a dispersion of 1650 ps/nm compared to the 450 ps/nm accumulated dispersion on 100 km of NZDF. Consequently, a module with a fiber designed to compensate the dispersion of NZDF will need a shorter length of dispersion compensating fiber and less loss will be added to the system.

Thus, the two strategies for increasing the figure of merit is to either decrease the attenuation of the dispersion compensating fiber or to increase the negative dispersion.

There are however limitations to how negative a dispersion is desirable. Dispersion compensating fibers with dispersions as negative as –1800 ps/(nm km) have been demonstrated, [11,12] but as this very negative dispersion can only be reached within a very narrow wavelength range, the dispersion properties of such a fiber will be very sensitive to variations in core diameter during manufacturing. Consequently, this design of a dispersion compensating fiber is not very desirable for a fiber manufacturer.

Other reports of dispersion compensating fibers that have more manufacturable designs include a fiber with a dispersion of –295 ps/(nm km), a FOM of 418 ps/(nm dB) and a RDS of 0.0004 nm^{-1} [13]. Another fiber has a negative dispersion of –302 ps/(nm km), a FOM of 459 ps/(nm dB) and a RDS of 0.0097 nm^{-1}.[14] None of these dispersion compensating fibers with high FOM published in the literature have slope match to SSMF.

4.1. Understanding the Attenuation of Dispersion Compensating Fibers

The attenuation of dispersion compensating fibers is typically in the range 0.4–0.7 dB/km depending on the fiber design. These values are high compared to the attenuation of less than 0.2 dB/km observed in transmission fibers.

The excess loss in dispersion compensating fibers is mainly design dependent, with bend and scattering losses as the main components. The attenuation of silica based optical fibers can be expressed as a sum of contributions:

$$\alpha_{\mathrm{tot}} = \alpha_{\mathrm{UV}} + \alpha_{\mathrm{IR}} + \alpha_{\mathrm{abs}} + \alpha_{\mathrm{scattering}} + \alpha_{\mathrm{waveguide}} \tag{27}$$

with α_{UV} being the attenuation due to absorption on electronics transitions, α_{IR} the attenuation due to multiphonon absorptions, α_{abs} the attenuation due to absorption on impurities or defects, $\alpha_{\mathrm{scattering}}$ the attenuation due to scattering and $\alpha_{\mathrm{waveguide}}$ the waveguide dependent attenuation.

The contributions to the attenuation from the first three terms in Equation 27 are roughly the same for both transmission and dispersion compensating fibers. It is mainly due to the last two terms $\alpha_{\mathrm{scattering}}$ and $\alpha_{\mathrm{waveguide}}$ that the dispersion compensating fibers have the high attenuation.

4.2. Attenuation Due to Scattering

The scattering losses of dispersion compensating fibers depend on fabrication method as well as the design of the fiber.

The scattering loss in germanium doped silica glasses can be expressed as

$$\alpha_{\mathrm{scattering}} = \alpha_{\mathrm{dens}} + \alpha_{\mathrm{conc}} + \alpha_{\mathrm{Bril}} + \alpha_{\mathrm{Raman}} + \alpha_{\mathrm{anomalous}} \tag{28}$$

α_{dens} being the elastic scattering due to density fluctuations in the glass, α_{conc} being the elastic scattering from concentration fluctuations, α_{Bril} being Brillouin scattering from acoustic phonons, α_{Raman} the scattering from optical phonons and $\alpha_{\mathrm{anomalous}}$ the scattering seen in fibers with a high index core. The first four contributions to the scattering losses show the same wavelength dependence:

$$\alpha_{\mathrm{scattering}} = \frac{C_{\mathrm{scattering}}}{\lambda^4}. \tag{29}$$

$C_{\mathrm{scattering}}$ being the scattering coefficient, which depends on glass composition and processing conditions. [15]

As $\alpha_{\mathrm{Raman}}$and α_{Bril} are both small compared to the other scattering losses, they will not be discussed further.

The scattering on density fluctuations (α_{dens}) is observed in all glasses. Density fluctuations are sometimes described as the dynamic fluctuations of the glass in the liquid state frozen in at the glass transition temperature (T_g). [16,17] The magnitude of the scattering on density fluctuations has been shown to be proportional to T_g, which is the temperature where a glass upon cooling reaches a viscosity of 10^{13} P. $T_g$depends on the cooling rate and the scattering due to density fluctuation can be lowered by controlling temperature during the fiber draw. [18,19]

α_{conc}, the scattering on concentration fluctuations, is observed in multicomponent glasses. In all glasses containing more than one component, regions will exist where the concentration of one component is higher than the other. As the germanium concentration in the core increases, so does α_{conc}. [20]

The correlation lengths for the scatterings causing α_{dens} and α_{conc} are small compared to the wavelength of light. They are sometimes referred to as Rayleigh scattering due to the wavelength dependence of $1/\lambda^4$.

When the index of the core is increased, the scattering losses increases faster with germanium concentration than can be explained by the Rayleigh losses. This is due to another type of scattering losses, which are responsible for a large part of the added attenuation of dispersion compensating fibers: The anomalous loss.

The term $\alpha_{\mathrm{anomalous}}$ of Equation 28 is the scattering on fluctuations of the core diameter, which are induced during draw. The fluctuations causing the scattering are of larger than, but typically of the same order of magnitude as, the wavelength of the light in the longitudinal direction of the fiber while the fluctuations in the radial direction is smaller than 1 nm. For step index fibers with a high core index, $\alpha_{\mathrm{anomalous}}$ is the largest contribution to the total loss of dispersion compensating fibers. For a fiber with core diameter d_{core}, core index n_{core} and gradient of core profile γ, the anomalous scattering loss is

$$\alpha_{\mathrm{anomalous}} = D_{\mathrm{anomalous}} n_{\mathrm{core}}^2 \frac{\gamma^2}{d_{\mathrm{core}}^m \lambda^k (\gamma+2)^2} \tag{30}$$

with $D_{\mathrm{anomalous}}$ being the strength of the scattering. The exponents m and k depends on γ as shown in Table 2. According to Eq. (30) the anomalous loss can be lowered by decreasing the core index or by grading the core [21].

Table 2. Exponents for the anomalous loss expression.

γ	**m**	**k**
2 (quadratic index profile)	1.6	2.4
∞ (Step index profile)	1	3

For fibers produced using the Modified Chemical Vapor Deposition (MCVD) process, the central dip in the index profile contributes to the scattering losses as well. It has been shown [22,23] that scattering losses can be reduced significantly if the central dip is eliminated.

4.2.1. Waveguide dependent attenuation:

The last term in Eq. (27) is $\alpha_{\mathrm{waveguide}}$, the waveguide dependent attenuation. The most important contributions are macro and micro bend losses.

Macro bend losses. A dispersion compensating fiber in a module is used on a spool with a typical inner diameter of 100–200 mm. The propagation in the bend fiber can be described using the equivalent index profile: [24]

$$n_{\mathrm{equ}}^2 = n^2(r)\left[1 + 2\frac{r}{R}\cos(\phi)\right] \tag{31}$$

with $n(r)$ being the index profile of the undistorted fiber, r and ϕ the cylindrical coordinates of the fiber and R the bend radius of the fiber.

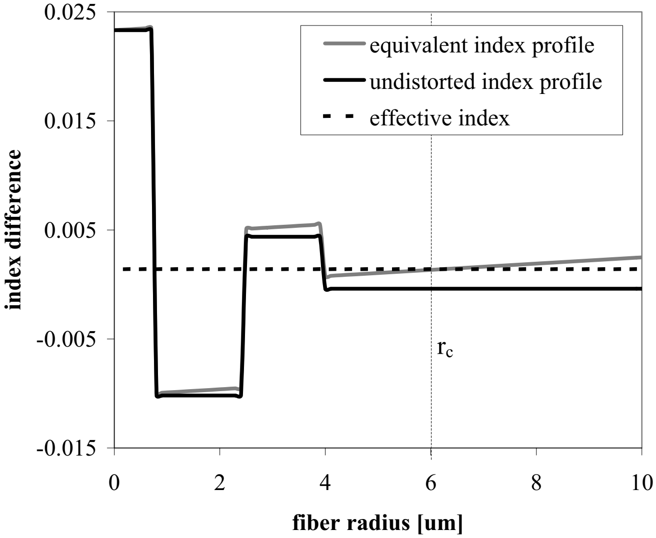

Fig. 9. The undistorted and the equivalent index profiles of a bend fiber. The vertical dotted line (rc) marks the radiation caustic, the radius where the mode becomes radiating.

The radius where the effective index intersects the equivalent index profile is the radiation caustic (r_c) outside which the field becomes radiating (Fig. 9). The macro bend losses can be reduced by either increasing the effective index, thereby increasing the radiation caustic, or by reducing the magnitude of the field at r_c by decreasing the effective area of the mode.

A side effect of increasing the effective index of the LP_{01} mode is that also the higher order modes will be more confined to the core thereby increasing their cut off wavelength. If the fiber supports higher order modes as well as the fundamental mode, the light traveling in the different modes can interfere, leading to noise due to modal MPI (multi path interference).

An interesting effect of bending the fiber is that as the propagation in the fiber changes with bend diameter so does the dispersion of the fiber. [26] It has been shown how the negative dispersion can be increased with decreasing bend diameters. [25,26] Unfortunately, this effect is most pronounced at the higher wavelengths where the effective index is small and the macro bend losses are high. It has been demonstrated on a multimoded dispersion compensating fiber where the minimum of the negative dispersion was shifted 40 nm by changing the bend radius from 6.6 to 25 cm. Since the change of dispersion is accompanied by a substantial increase of the fiber loss, it is unlikely that this effect can be utilized for making tunable dispersion compensating fibers. [27]

Micro bend losses. The fiber in a module experiences not only the macroscopic bend loss induced by the bend radius of the fiber on the module. Another source of attenuation is the micro bend loss originating from the microscopic deformations caused by the pressure from the other fibers in the package.

The micro bend loss of the fiber is important not only for the overall attenuation of the fiber, but also for the performance of the dispersion compensating fiber module when subjected to temperature changes. When the dispersion compensating fiber module is subjected to an increase of temperature, the metallic spool on which the fiber is wound, will expand. The fiber will experience a pressure from the other turns of the fiber, which will act as a surface with deformation power spectrum Φ. This leads to microbend loss (α_{micro}) that can be expressed as [28]:

$$2\alpha_{\mathrm{micro}} = \sum_{p} C_{1p}^{2}\Phi(\Delta\beta_{1p}), \tag{32}$$

where C_{1p} are the coupling coefficients between the LP_{01} mode and the cladding mode, LP_{1p} , ($p = 1, 2,\ldots$) and Φ is the deformation power spectrum of the fiber axis at spatial frequencies $\Delta\beta_{1p}$ corresponding to the difference in propagation constants between the LP_{01} and cladding modes ($\Delta\beta_{1p} = \beta_{01} - \beta_{1p}$).

The deformation spectrum experienced by the fiber depends on the stiffness of the fiber as well as of the ability of the coating to absorb the deformation. This leads to an expression for the micro bend loss of a fiber that experiences a linear pressure (F) onto a surface with the deformation spectrum Φ[29]:

$$2\alpha_{\mathrm{micro}} = \sqrt{\frac{2}{\pi}\frac{DF}{H^{2}\sigma}}\sum_{p=1}^{\infty} C_{1p}^{2}\frac{1}{(\Delta\beta_{1p})^{8}}\Phi_{s}(\Delta\beta_{1p}) \tag{33}$$

with σ being related to the RMS value of the surface deformation, H the flexural rigidity (stiffness) and D the lateral rigidity of a coated fiber. The terms in front of the summation are all related to the mechanical properties of the fiber, whereas the terms inside the summation are related to the fiber index profile and the deformation spectrum.

Equation (33) shows that by increasing the fiber diameter and thereby the stiffness of the fiber, the micro bend losses can be reduced. Another possibility for reducing the micro bend losses is to change the ability of the coating to protect the fiber from deformation by absorbing the pressure.

As the terms inside the summation shows, the micro bend loss depends strongly on the difference in propagation constants ($\Delta\beta_{1p}$). So by choosing a design with large effective index difference, the micro bend loss can be minimized.

Splice losses. The second term in Eq. (25) describing the total loss of a dispersion compensating fiber module, α_{splice} is the losses arising from the splice between the dispersion compensating fiber and the standard single mode fiber pigtails. As the propagation of light in dispersion compensating fibers tend to be very sensitive towards small perturbations of the index profile, any such perturbations during the splice will induce some of the light to couple into higher order modes and increase the loss. The main problem lies in the fact that the small, non-Gaussian mode field of the dispersion compensating fiber must match the much larger Gaussian mode field of the standard single mode connector in order to yield low splice losses.

To reduce the splice losses several techniques have been proposed. By using Thermally Expanded Core (TEC) splicing, [32] tapering of the fusion splice [33] or fattening the fusion splice [34] the cores of the dispersion compensating fiber and the standard single mode fiber can be modified to facilitate a smooth transition from one fiber to the other and thus minimize the splice losses. Another method uses an intermediate fiber, which can be spliced between the dispersion compensating fiber and the standard single mode fiber with a low loss. [35]

The different contributions to the attenuation of dispersion compensating fibers mentioned in the previous section all depend on the core index, but in different ways. If the core index is increased, the attenuation due to Rayleigh scattering and anomalous loss increases as well. The bend losses on the other hand decreases with higher core index as the effective index becomes higher and the light is more confined to the core, which again leads to a higher cutoff wavelength for the higher order modes.

This represents some of the trade offs encountered for the design of dispersion compensating fibers with high figure of merit. As will be shown in the next section, even more trade offs are introduced when the dispersion is considered as well.

4.3. Increasing the Negative Dispersion

Another way to lower the total losses of a dispersion compensating fiber module is to decrease the length of the dispersion compensating fiber [Eq. (25)]. This can be done by increasing the negative dispersion on the dispersion compensating fiber [Eq. (26)].

As discussed in a previous section, the dispersion curve can be moved with respect to operating wavelength by scaling the core. By changing only the trench, the dispersion curve can be made deeper and narrower without changing the area above the dispersion curve. These two operations can be used to increase the negative dispersion considerably and thereby show a way to increase the figure of merit.

Figure 10(a) shows the dispersion properties of two commercially available dispersion compensating fibers both with slope match to SSMF at 1550 nm. Fiber A has a dispersion of –120 ps/(nm km) while fiber B has a dispersion of –250 ps/(nm km).

The very negative dispersion of fiber B has been obtained by making the dispersion curve deeper and narrower by increasing the negative index of the trench (Fig. 11). Due to the low index of the trench region of fiber B, the overlap between the core and ring mode is small resulting in a high curvature of the effective index and consequently a very negative dispersion. The dispersion curve has been moved with respect to the operating wavelength by increasing the width of the core.

The measured optical properties of the two fibers at 1550 nm are shown in Table 3. Even though the dispersion of fiber B is more than twice as negative as that of fiber A, the attenuation has also increased from 0.43 dB/m to 0.58 dB/m so the figure of merit has only increased from 280 ps/(nm dB) to 430 ps/(nm dB).

Part of the increased attenuation can be explained by the higher anomalous loss due to the larger index difference between core and trench. Another part is due to increased bend loss sensitivity.

Figure 10(b) shows the simulated effective index difference and effective area for the two fibers. At 1550 nm, the effective index difference of fiber B is close to that of the ring mode. As the wavelength increases, the effective index difference decreases, thereby moving the radiation caustic closer to the core. This gives fiber B a high macro bend loss. The effective index difference of fiber A is larger, and the macro bend losses for this fiber are consequently much smaller.

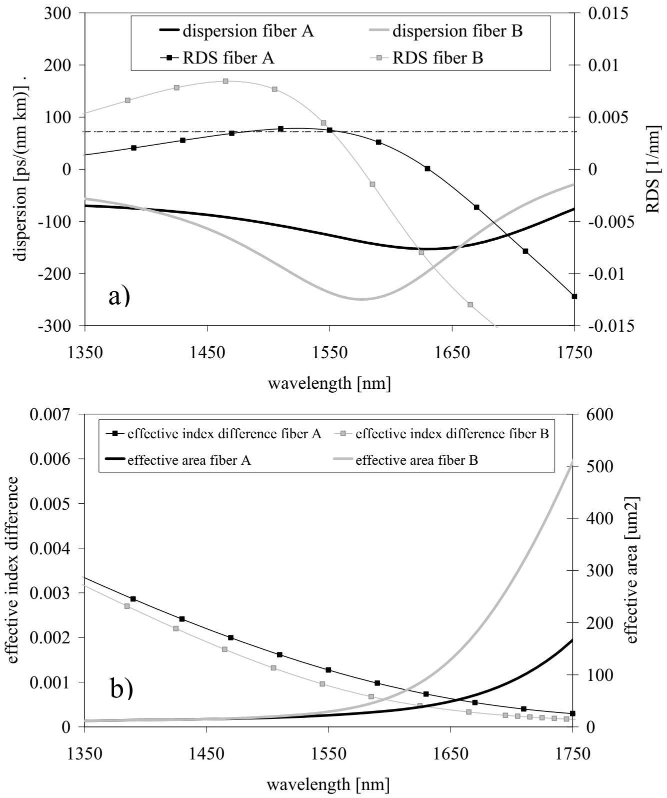

Fig. 10. Dispersion, RDS, effective index difference and effective area of the A and B fibers. Both fibers have an RDS of 0.0035 nm^{-1} at 1550 nm matching that of SSMF. Due to a higher curvature of the effective index of fiber B, the dispersion has been increased from the –120 ps/(nm km) of fiber A to –250 ps/(nm km).

Another consequence of the higher effective index difference of fiber A is that the micro bend losses for this fiber is lower than that of fiber B and consequently the stability of the fiber towards temperature changes is high.

Another draw back for fiber B is the higher residual dispersion. As the operating wavelength of fiber A is close to the inflection point of the dispersion curve, the curvature is very low whereas fiber B operates where the dispersion curvature is high resulting in a high residual dispersion.

A high residual dispersion is not the only consequence of the high dispersion curvature of fiber B. With a high curvature, the change in RDS with wavelength is high and the fiber is consequently very sensitive to the small variations in core diameter that are unavoidable during fiber production. In Fig. 12 the variation of RDS with core diameter is shown for fiber A and fiber B. Whereas the RDS of fiber A is relative insensitive to small variations of core diameter, even small variations of the

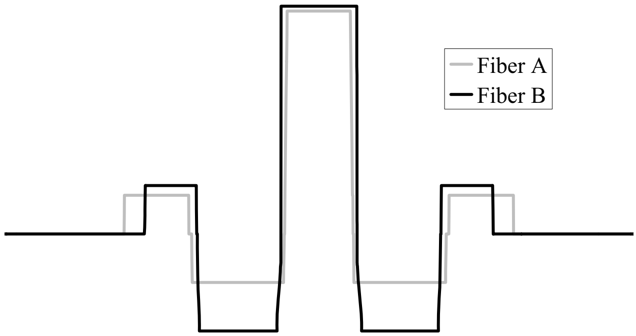

Fig. 11. Representative profiles for fibers A and B. The main difference between the index profiles of the two fibers is the refractive index of the trench region. Due to the lower refractive index of the trench region of fiber B, the overlap between the core and the ring mode is small resulting in a high curvature of the effective index and consequently a very negative dispersion.

Table 3. Optical properties measured at 1550 nm for 3 dispersion compensating fibers with slope match to standard single mode fiber (RDS = 0.0035 nm^{-1})

		Dispersion (ps/nm km)	Attenuation (dB/km)	Typical splice loss (dB)	FOM (ps/nm dB)	Residual dispersion variation (1530–1565 nm) (ps/nm km)
DCF A	Conventional DCF for SSMF	–120	0.43	0.35	280	±0.02
DCF B	High FOM DCF for SSMF	–250	0.58	0.2	430	±0.2
DCF C	Low loss DCF for SSMF	–170	0.46	0.3	370	±0.1

core diameter of fiber B changes the RDS so slope match to SSMF can no longer be obtained.

The dispersion properties of fiber B are not the only properties that are very sensitive to variations of the core diameter. As shown previously (section 3) changing the core diameter corresponds to moving the dispersion curve with respect to wavelength. Consequently all other properties that change rapidly with wavelength will be very sensitive to any variations of the core diameter. This includes the effective area [Fig. 10(b)] and consequently the macro bend losses.

It is important however to keep in mind that even with the draw backs for fiber B presented above, it does have a higher figure of merit than fiber A, and for some applications a low attenuation of the dispersion compensating fiber module is more important than a low residual dispersion and high usable bandwidth.

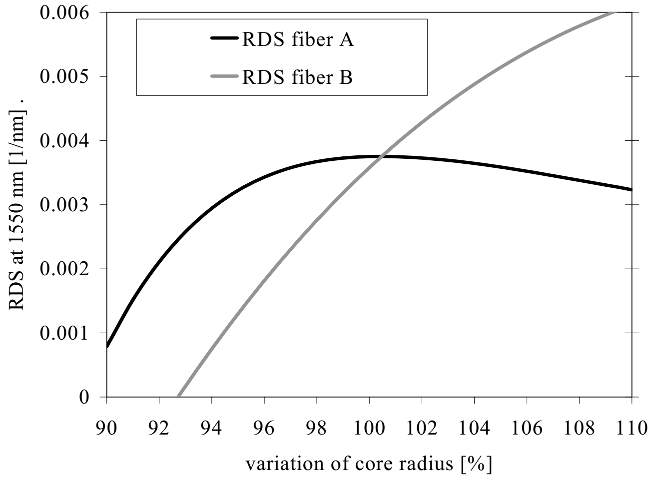

Fig. 12. RDS for fiber A and fiber B as function of variations of core radius. The RDS of fiber A is not very sensitive to variations in core radius, while for fiber B even small variations in core radius changes the RDS so slope match to SSMF can no longer be obtained.

Fibers A and B has been presented as representatives for two different design strategies: Optimizing the residual dispersion (fiber A) or optimizing the figure of merit (fiber B). It is of course possible to design a fiber that is somewhere in between the two. Fiber C of Table 3 is an example of such a fiber.

Figure 13 shows the residual dispersion variation of fibers A, B and C. Fiber C is designed to have both a high figure of merit of 370 ps/(nm dB) and a low residual dispersion of only ± 0.1 ps/(nm km). The low residual dispersion has been achieved by operating below, but closer to the inflection point than fiber B. Even though the dispersion at the inflection point is not as negative as that seen for fiber B, the figure of merit is high as the attenuation of the fiber is lower due to a design that is optimized with respect to the waveguide dependent losses.

As the fiber does not operate as close to the minimum of the dispersion curve as fiber B, more of the field is confined to the core resulting in lower bend losses. The index profiles has furthermore been optimized with respect to anomalous losses [Eq. (30)] by choosing a core index and core gradient that will give the right dispersion properties while minimizing the anomalous losses.

5. Dispersion Compensating Fibers with High Dispersion Slope

The dispersion compensating fibers described in the previous sections have all been designed to compensate the dispersion of standard single mode fiber (SSMF), which are the most commonly used type of fiber. As listed in Table 1 several other types of transmission fibers exist.

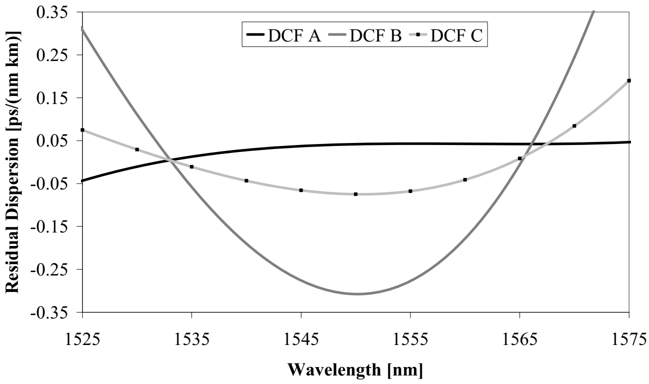

Fig. 13. Residual dispersion for SSMF compensated with fibers A, B or C. Fiber A is optimized for low residual dispersion. Fiber B is a high FOM fiber optimized to have a very negative dispersion. Fiber C is an intermediate fiber of A and B with a medium FOM and residual dispersion slightly higher than that of fiber A.

Historically, the dispersion shifted fibers (DSF) were designed to have zero dispersion at 1550 nm where the attenuation in silica fibers is lowest. For multi channel systems however, zero dispersion is a disadvantage since four wave mixing can occur between channels, resulting in interchannel crosstalk, which degrades the system performance. Currently, DSF is used mainly in the L-band where the dispersion is in the order of 2.8 ps/(nm km) and the RDS in the order of 0.025 nm^{-1} at 1590 nm.

The NZDF was designed to have less dispersion than SSMF at 1550 nm, but still enough dispersion to eliminate problems with four wave mixing. As shown in Table 1, they all have dispersion lower than 8 ps/(nm km) while the RDS values can be as high as 0.02 nm^{-1}.[30]

Even though the dispersion of the NZDF is reduced compared to SSMF, at high bit rates there is still a need for compensating this dispersion.

The dispersion of NZDF with RDS less than 0.01 nm^{-1} proves no challenge to compensate. [31] It has however proved to be a challenge to design dispersion compensating fibers for the NZDFs with RDS values above 0.01 nm^{-1} especially those where the RDS reaches values in the order of 0.02 nm^{-1}. [32–34]

5.1. Design

The basic index profile of dispersion compensating fibers with high dispersion slope is the triple clad index profile of Fig. 5. The complicated design of these fibers involves many trade offs especially between the dispersion properties and bend losses.

As an understanding of the different trade offs involved can be gained by investigating the effects of only changing a few parameters of the index profile, in this section only the width of the core and trench layer of the index profiles will be changed.

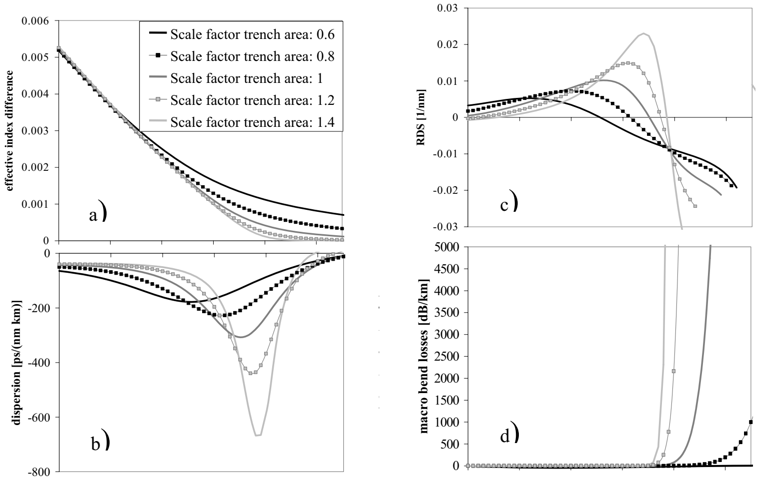

Fig. 14. The effect on effective index, dispersion, RDS and macro bend losses of changing the area of the trench of the triple clad index profile. (a) Increasing the area of the trench decreases the overlap between the core and ring mode. This causes an increase of the curvature of the effective index, resulting in a deep and narrow dispersion curve (b) with a high dispersion slope and consequently a higher RDS (c) Increasing the area of the trench reduces the wavelength for max RDS. The opposite effect is seen for the macro bend losses where the macro bend losses increases with increasing trench area (d) making the bandwidth, where the fiber has both a high RDS and low macrobend losses, very narrow.

The effect of changing the width of the trench from 0.6 to 1.4 (arbitrary units) on the dispersion, the RDS, the effective index difference and the macro bend losses as functions of wavelength is shown in Fig. 14.

When the diameter of the trench is increased, the overlap between core and ring modes is decreased and curvature of the effective index difference is increased resulting in a very negative dispersion [Eq. (9)]. As discussed in section 2, when the slope of the effective index difference remains largely unchanged at both the lower and higher wavelengths, the area above the dispersion curve must remain unchanged as well resulting in a more narrow dispersion curve with a high dispersion slope and consequently the possibility for high RDS values [Fig. 14(b)] shows the effect on macro bend losses of increasing the width of the trench. As the width of the trench increases, the wavelength for max RDS is reduced. The opposite effect is seen for the macro bend loss. When the width of the trench increases, so does the wavelength where the attenuation, due to macro bend losses become large making the bandwidth where the fiber has both a high RDS value and low losses very narrow. This can to some extend be counteracted by increasing the effective index, thereby increasing the radiation caustic. However, as for the fibers with high figure of merit, increasing the effective index will result in a higher cutoff wavelength, as higher order modes will be better confined to the core as well.

An important question is: When is the cutoff wavelength for the higher order modes too high? An investigation of the relation between cutoff wavelength and MPI

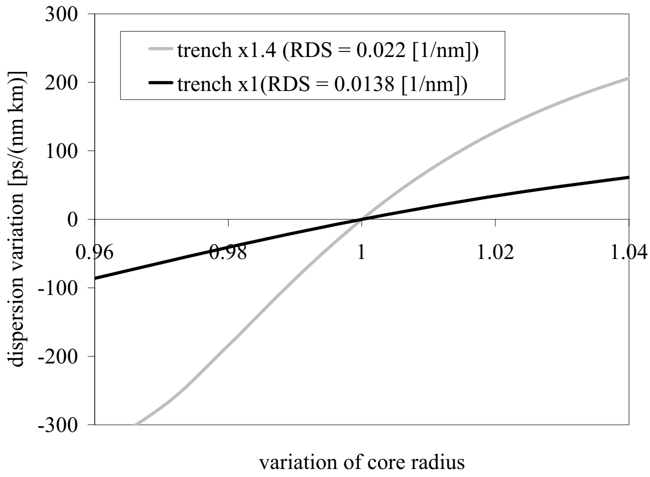

Fig. 15. Dispersion variation at the inflection point for two different scalings of the width of the trench. The sensitivity of the dispersion with respect to variation of the core radius is increased for increased width of the trench.

has been performed showing how dispersion compensating fibers with high dispersion slope have a higher MPI than dispersion compensating fibers with low dispersion slope, probably due to the higher cutoff wavelength of the high slope dispersion compensating fibers. [35] However, the investigation gives no conclusive answer as to what the maximum acceptable cutoff wavelength is with respect to MPI.

Another question is how to correctly measure the cutoff of dispersion compensating fibers. The cutoff wavelength can be considered as the wavelength where the higher order modes experience bend losses high enough so they no longer can be considered as being guided. This wavelength will of course depend on the bend diameter of the fiber on the module and the measurement of the cutoff wavelength will depend on the length of fiber measured as well. [36,37] The bending diameter of the dispersion compensating fiber during the measurement of the cutoff wavelength should be chosen to be slightly larger than the outer diameter of the dispersion compensating module thereby ensuring single mode operation of the fiber above the measured cutoff wavelength when the fiber is on the spool in the module.

Increasing the RDS by increasing the width of the trench not only increases the macro bend sensitivity of the fiber; it also increases the sensitivity of the dispersion to small variations in core diameter. Figure 15 shows the dispersion variation at the inflection point for two different scalings of the trench resulting in RDS values of 0.022 nm^{-1} and 0.0138 nm^{-1}. The scale factors for the width of the trench are given in the figure.

Naturally, as the dispersion slope increases, so does the sensitivity to small changes in core diameter, which makes it challenging to manufacture dispersion compensating fibers with high dispersion slopes.

Another trade off is the limitations imposed on the usable bandwidth by increasing the dispersion slope. [6,10] It was found that for fibers designed to operate at a wavelength close to the inflection point there is an inverse relationship between the usable bandwidth and RDS. This is true as long as the effective indices of the core and ring mode do not change significantly from fiber to fiber. If the effective indices of the core and ring mode do not change, the area above the dispersion curve is kept constant. Consequently, increasing the dispersion slope will cause the dispersion curve to become deep and narrow, thus decreasing the usable bandwidth. If the index of the core or ring region is changed, this relationship will no longer hold.

5.2. *Combined Dispersion Compensating Fiber Module*

Another possibility for making a dispersion compensating fiber module with a high dispersion slope is to use a combined module where the desired dispersion properties are obtained by combining two different fibers [38].

The dispersion of the combined module is

$$D_{\text{combined}} = D_{\text{DCF1}} L_{\text{DCF1}} + D_{\text{DCF2}} L_{\text{DCF2}} \tag{34}$$

and the slope is

$$S_{\text{combined}} = S_{\text{DCF1}} L_{\text{DCF1}} + S_{\text{DCF2}} L_{\text{DCF2}}. \tag{35}$$

Leading to a relative dispersion slope (RDS) for the combined module of:

$$\text{RDS}_{\text{combined}} = \frac{S_{\text{DCF1}} L_{\text{DCF1}} + S_{\text{DCF2}} L_{\text{DCF2}}}{D_{\text{DCF1}} L_{\text{DCF1}} + D_{\text{DCF2}} L_{\text{DCF2}}}. \tag{36}$$

If the two fibers in the combined module have negative dispersion it is possible to make a combined module with a RDS value between that of the two individual fibers. If however fiber 1 has a negative dispersion and fiber 2 a positive dispersion but a RDS value lower than that of fiber 1, it is possible to achieve a RDS for the combined module that is higher than the RDS of fiber 1. Consequently a dispersion compensating fiber module with a RDS value matching that of the high slope NZDF can be manufactured by combining a dispersion compensating fiber having a low RDS value of 0.015 nm^{-1} with for example SSMF fiber having a positive dispersion and a RDS of 0.0036 nm^{-1}.

As shown previously, a dispersion compensating fiber with a lower RDS is less sensitive to variations in core diameter and less likely to suffer from high macro bend losses. By using the method of the combined module it is thus possible to make a dispersion compensating fiber module with slope match to the high slope NZDF using a dispersion compensating fiber with a lower RDS.

As the length of both fibers in the combined module increases with the difference between $\text{RDS}_{\text{combined}}$ and RDS_{DCF1}, so does the attenuation of the module. This is however in some instances preferred to the difficulties associated with the production of a dispersion compensating fiber with slope match to the high slope NZDFs.

One of the reasons the combined module can offer an attractive solution, not only to the user, but also to the manufacturer is that the combination of two different fibers in the module can reduce the width of the RDS distribution as shown in Fig. 16. As the RDS of the combined module is controlled by the length of positive dispersion fiber, better control of the RDS can be achieved for the combined than for a single fiber solution.

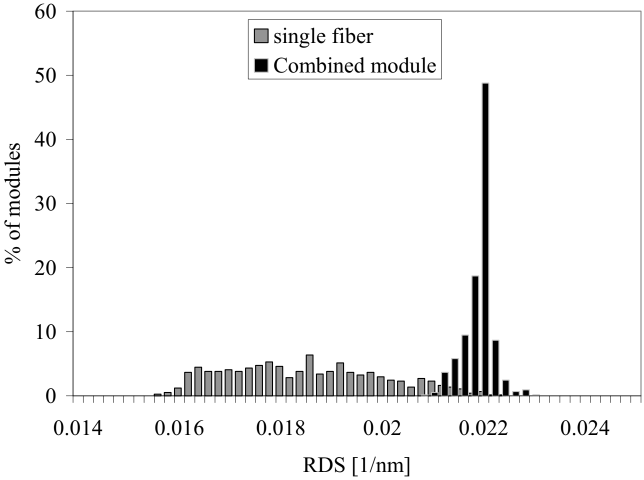

Fig. 16. The distribution of RDS values for the negative dispersion fiber and for the combined module. By making a combined module, the RDS distribution is narrowed significantly.

6. Dispersion Compensating Fiber Module with Reduced Physical Dimensions

In the previous sections the trade offs between dispersion properties and bend losses have been explored in order to design fibers with extreme dispersion properties such as a very negative dispersion or a high dispersion slope. It was found that the performance with respect to bend loss limits the obtainable dispersion properties.

The minimization of bend losses is also central when it comes to reducing the physical dimensions of a dispersion compensating fiber module.

Several approaches exist to reducing the size of the dispersion compensating fiber module. The approach to be discussed in this section is to reduce the diameter of the fiber *A*nd the inner diameter of the spool on which the fiber is wound in the dispersion compensating fiber module. Another strategy is to look at the packaging of the fiber in the dispersion compensating fiber module in order to reduce the microbend losses. [39,40]

6.1. Bend Losses

No matter how the challenge of decreasing the physical dimensions is approached, bend loss will limit the design:

If the approach to smaller physical dimensions is to decrease the fiber and/or coating diameter thereby decreasing the fiber volume, the microbend losses will be the limiting factor.

For a given fiber design Equation 33 reduces to

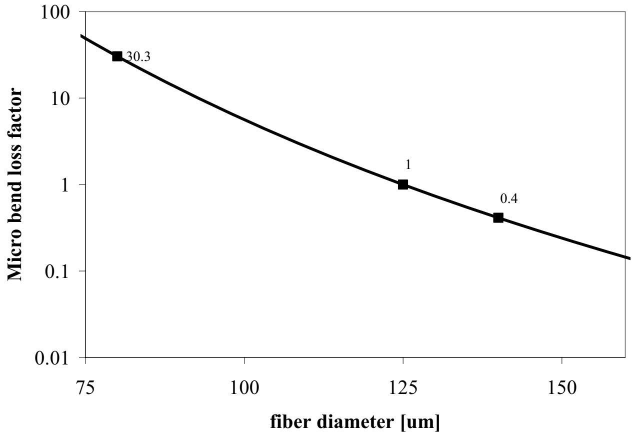

Fig. 17. Simulated micro bend loss factor as a function of fiber cladding (glass) diameter. The thickness of the coating is kept constant.

$$\alpha_{\mathrm{micro}} \propto \frac{D}{H^2}. \tag{37}$$

For a given fiber design, the micro bend losses can be evaluated for different flexural and lateral rigidities of the fiber.

Expressions for the flexural rigidity (H) and lateral rigidity (D) of a double coated fiber has been derived in terms of the Young's modulus and the diameter of the fiber, primary and secondary coating layers [41]:

$$H = H_{\mathrm{glass}} + H_{\mathrm{sec.coat}} = \pi r_{\mathrm{glass}}^4 E_{\mathrm{glass}} + \pi (r_{\mathrm{sec.coat}}^4 - r_{\mathrm{prim.coat}}^4) E_{\mathrm{sec.coat}} \tag{38}$$

and

$$D = E_1 + (E_2 - E_1)\left(\frac{E_1}{E_2}\right)^{2/3}\left(2\frac{r_2 - r_1}{r_2 - r_0}\right)^{2/3} \tag{39}$$

with E being Young's modulus and r the radius of the layer. Subscript 0 refers to the fiber, 1 to the primary coating and 2 to the secondary coating.

Figure 17 shows the micro bend loss as a function of fiber diameter for a given fiber design with the loss normalized to that of a fiber with diameter of 125 μm and a constant thickness of the coating layers.

If the fiber diameter is reduced from 125 to 80 μm, the microbend loss increases with a factor of 30. In order to achieve similar micro bend losses in an 80-μm fiber As in a 125-μm fiber, the micro bend loss performance must be increased by a factor of 30.

Another interesting point is that by increasing the fiber diameter, the microbend loss is improved. This effect has been utilized to fabricate a dispersion compensating fiber with high dispersion slope. The fiber diameter was increased to 140 μm thereby decreasing the microbend losses for an otherwise micro bend sensitive design. [34]

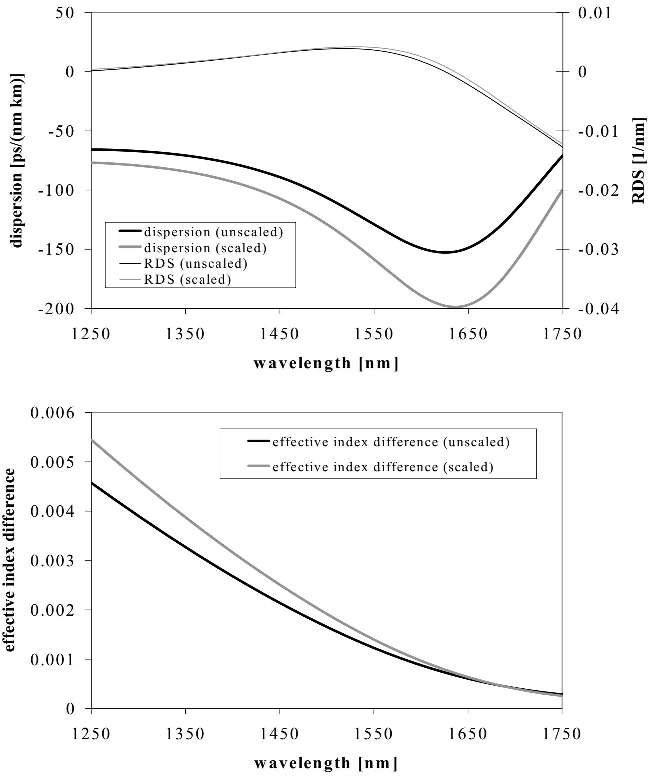

Fig. 18. The dispersion properties and effective index difference of a dispersion compensating fiber scaled as described in equation 12. By scaling the indices of all layers of a triple clad index profile with 1.2 and the areas of all layers by $1/\sqrt{1.2}$ both the effective index and the dispersion have been increased by a factor of 1.2 (Neglecting the material dispersion causes an error on the scaled dispersion of 3.7 ps/nm km). The only change in RDS due to the scaling of the profile is caused by the neglect of the material dispersion.

The main approach to improving the micro bend loss sensitivity of the dispersion compensating fiber is to increase the effective index difference.

The scaling outlined in section 3 [Eqs. (15)–(23)] shows how the effective index difference can be increased without significantly changing the dispersion properties.

Figure 18 shows the dispersion, RDS and effective index difference of two dispersion compensating fibers, where the scaled profile has been obtained from the unscaled by scaling the refractive indices of each layer by 1.2 and the widths by $1/\sqrt{1.2}$.

The RDS are almost unchanged by the scaling, while a large increase in effective index difference is observed, resulting in improved calculated micro bend losses of a factor of 5. [42] The error on the dispersion by neglecting material dispersion is of 3.7 ps/(nm km). This scaling is however not ideal as it would require the index of the core to be increased by 20% which would greatly increase the attenuation of the fiber due to anomalous losses and Rayleigh scattering.

As discussed previously, increasing the effective index difference not only reduces the micro bend loss sensitivity, it also reduces the macro bend losses of the fiber.

The approach of increasing the effective index difference has been used to make a dispersion compensating fiber module with slope match to SSMF with reduced physical dimensions. [43] The properties of the fiber are listed in Table 4.

Table 4. Optical properties measured at 1550 nm for a dispersion compensating fiber with slope match to standard single mode fiber (RDS = 0.0035 nm^{-1}) and reduced physical dimensions.

	Dispersion (ps/nm km)	Attenuation (dB/km)	Typical splice loss (dB)	FOM (ps/nm dB)	Fiber diameter (μm)	Coating diameter (μm)	Residual dispersion variation (1530–1565 nm) (ps/nm km)
DCF for SSMF with reduced physical dimensions	–123	0.59	0.1	210	80	145	±0.02

The dispersion properties are comparable to that of fiber C of Table 3. Due to a higher core index, the attenuation is somewhat higher resulting in a FOM of only 210 ps/(nm dB). However, due to the improved bend loss performance, it has been possible to manufacture a dispersion compensating fiber module for compensating the dispersion of 70 km SSMF with a height of 22 mm and an outer diameter of 140 mm, which compared to an ordinary dispersion compensating fiber module with a height of 40 mm and an outer diameter of 199 mm, is a 4× reduction of the volume. Figure 1 shows a dispersion compensating fiber module with reduced physical dimensions in front of an ordinary module.

Since the design of the dispersion compensating fiber with reduced physical dimensions will be limited by the bend loss sensitivity, it will be more difficult to make a fiber that has both the reduced physical dimensions and extreme dispersion properties such as a very high dispersion slope or a very negative dispersion.

7. Nonlinear Phaseshift of Dispersion Compensating Fiber Modules

So far, the quality of a dispersion compensating fiber module has only been evaluated on the residual dispersion and the added loss to the system.

Dispersion and added loss are however not the only parameters which degrade the signal to noise ratio of the system. It has been shown that in systems with a low residual dispersion, the degradation of the signal can be linked to the nonlinear phaseshift of the dispersion compensating fiber module, which should be as small as possible. [44]

The nonlinear phaseshift (ϕ_{NL}) in a dispersion compensating fiber module in the configuration shown in Fig. 2 can be expressed as

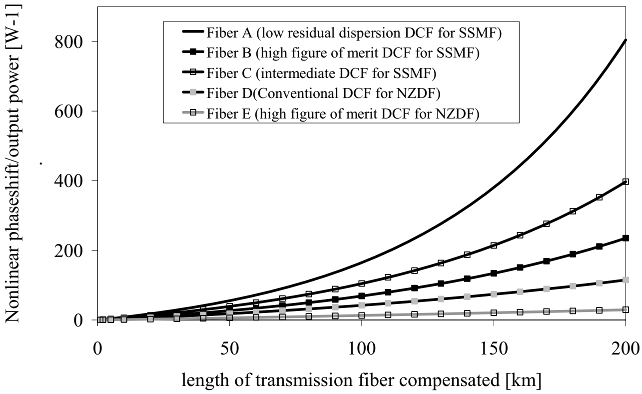

Fig. 19. The ratio of nonlinear phaseshift to output power as a function of length of transmission fiber compensated for dispersion compensating modules for SSMF and NZDF. The lowest nonlinear phaseshift is obtained for a high FOM dispersion compensating fiber module for NZDF.

$$\phi_{\mathrm{NL}} = \frac{2\pi n_2}{\lambda A_{\mathrm{eff}}} P L_{\mathrm{eff}} = \frac{2\pi n_2}{\lambda A_{\mathrm{eff}}} P_{in} \frac{(1 - \exp(-\alpha_{\mathrm{DCF}} L_{\mathrm{DCF}}))}{\alpha_{\mathrm{DCF}}} \tag{40}$$

with n_2 being the nonlinear refractive index, $\mathrm{A}_{\mathrm{eff}}$ the effective area, P_{in} the input power to the dispersion compensating fiber module and L_{eff} the effective length. If the output power is kept constant, the signal to noise ratio can be assumed to be constant and P_{in} can be expressed as

$$P_{\mathrm{in}} = P_{\mathrm{out}} \exp(\alpha_{\mathrm{DCF}} L_{\mathrm{DCF}} + \alpha_{\mathrm{spl}}). \tag{41}$$

The ratio of nonlinear phaseshift to output power can now be calculated as

$$\frac{\phi_{NL}}{P_{\mathrm{out}}} = \frac{n_2 2\pi}{\lambda\alpha\ A_{\mathrm{eff}}} \exp\left(\alpha \frac{D_{\mathrm{tot}}}{D_{\mathrm{DCF}}} + \alpha_{\mathrm{sp}}\right)\left(1 - \exp\left(-\alpha \frac{D_{\mathrm{tot}}}{D_{\mathrm{DCF}}}\right)\right). \tag{42}$$

Using Eq. (42) the ratio of nonlinear phaseshift to output power can be evaluated for modules with different dispersion properties. [45] Figure 19 shows the ratio of nonlinear phaseshift to output power for the dispersion compensating fibers with slope match to SSMF listed in Table 3 as well as for two dispersion compensating fiber for NZDF (Table 5) with RDS values of 0.01 nm^{-1} matching that of TrueWave ® RS. Fiber E has the highest figure of merit reported for a dispersion compensating fiber of 459 ps/(nm dB). [14] This fiber is an example of how it can be easier to obtain a high figure of merit for a dispersion compensating fiber with a higher dispersion slope.

The ratio is shown as a function of length of transmission fiber compensated. It has been calculated using data from Tables 3 and 4 and n_2 of 2.7 × 10^{-20} for all fibers. n_2 has been measured for several dispersion compensating fibers using the CW beat signal method. [46]

The ratio of nonlinear phaseshift to output power depends mainly on the length of dispersion compensating fiber in the module. Consequently, the lowest ratio can

Table 5. Optical properties measured at 1550 nm for dispersion compensating fibers with slope match to Non Zero Dispersion Fibers (RDS = 0.01 nm^{-1})

		Dispersion (ps/nm km)	Attenuation (dB/km)	Typical splice loss (dB)	FOM (ps/nm dB)
DCF D	Conventional DCF for NZDF	–120	0.63	0.35	170
DCF E	High figure of merit DCF for NZDF	–302	0.66	0.3	459

be found for the dispersion compensating fiber for NZDF with high figure of merit. Not only does the lower accumulated dispersion on NZDF calls for shorter lengths of dispersion compensating fiber but the very negative dispersion of –302 ps/nm km reduces the required length of dispersion compensating fiber further. This also explains that even though fiber D has the lowest figure of merit of the 5 fibers, the ratio of nonlinear phaseshift to output power is only slightly higher than that for fiber E.

A higher ratio is seen for fiber B with the high figure of merit for compensating SSMF. This is again due to the shorter length of fiber needed in the module. As the figure of merit decreases, the ratio of nonlinear phaseshift to output power increases giving fiber A the highest ratio of the five fibers.

The lower ratio of nonlinear phaseshift to output power for the dispersion compensating fiber with high figure of merit is mainly due to the shorter length of fiber needed in a module, so the same effect on the nonlinear phaseshift would not be observed if the improvement in figure of merit was due to an improvement of the attenuation of the dispersion compensating fiber. [40,47]

8. Summary

In this paper it has been shown how the dispersion properties of the dispersion compensating fiber can be tailored by scaling the index profile.

The trade offs associated with the design of dispersion compensating fibers with extreme dispersion properties such as a very negative dispersion or very high dispersion slope has been discussed and it has been found that the main trade offs is between the desired dispersion properties and properties such as manufacturability and bending losses.

If less extreme dispersion properties can be accepted, it is possible to optimize the bend loss to a degree that makes it possible to manufacture a dispersion compensating fiber module with reduced physical dimensions.

For the fiber with a high figure of merit it was shown how increasing the negative dispersion by operating closer to the minimum of the dispersion curve can give problems with bend losses as the effective index difference at this wavelength is low.

It was also shown how increasing the figure of merit by increasing the negative dispersion of the dispersion compensating fiber, thus decreasing the length of fiber needed in a module, improves the performance of the module with respect to nonlinearities.

For fibers with high dispersion slope, increasing the dispersion slope will cause the usable bandwidth to be smaller as the dispersion curve becomes narrower with increasing RDS. As for the dispersion compensating fibers with high figure of merit, the bend losses are usually high for this type of fiber. The improvement of macro bend losses will usually cause the cutoff wavelength to increase giving problems with MPI.

It has also been shown how a dispersion compensating fiber module with slope match to the high slope NZDFs (RDS = 0.02 nm^{-1}) can be manufactured by combining a dispersion compensating fiber having a lower RDS value with a positive dispersion fiber having a lower RDS than the dispersion compensating fiber. The advantages of this solution are a better control of the RDS of the module, and a dispersion compensating fiber with lower bend losses and better manufacturability.

Finally, by improving the bend loss performance a dispersion compensating fiber module with reduced physical dimensions have been manufactured.

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