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Design of dispersion flattened and compensating fibers for dispersion-managed optical communication systems

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Abstract

Single mode optical fibers having minimum non-zero dispersion over the spectral windows of 1300 and 1550 nm region are essential for the multi-channel operation of dense wavelength multiplexed systems and minimizing the nonlinear four wave mixing effects This paper demonstrates that non-zero dispersion flattening of the dispersion factor extends over a wavelength range of more than 350 nm is achievable. We present the design of the dispersion flattening of the non-zero dispersion fiber (NZ-DF) with minimum of dispersion factor, as well as dispersion compensating fiber (DCF) that allows complete dispersion compensation over entire S- to L-bands of the third communications window .The overall dispersion-length (DL) product of a fiber span can be tailored to be close to zero. Hence the designed composite fiber length of a "kappa" value of 1 with a DL product of zero for the span length of 100 Kms of the fiber is demonstrated. The effects of the geometrical and index distribution parameters of the triple-clad profile to sensitivity of the total dispersion factor of the DFF and DCF are analyzed. We also outline design guidelines for identifying the critical parameters and steps for tailoring the fiber dispersion property.

Key words: optical fibers; optical fiber dispersion; wavelength division multiplexed optical fiber systems, 40Gb/s transmission systems.

INTRODUCTION

Single mode optical fiber with minimum dispersion at the two optical windows in the 1300 nm and 1550 nm wavelength are expected to be critically important for ultra-long high-speed and ultra-high capacity optical communication systems and networks in the near future global internetworking. In particular for optical communications transmission system that employs wavelength multiplexing optical carriers. The demand to expand the transmission capacity requires investigation of wavelength division multiplexed telecommunications and the pulse broadening effects of optical fibers over the optical spectrum.

The availability of single mode optical fibers with a minimum and flattened characteristics in dispersion and insensitive to micro-bending loss and other additional losses will enhance the system engineering of these fibers. In addition the commercial availability of Er:doped fiber amplifiers have allowed system designers to investigate the use of near-zero dispersion optical fibers to extend the repeaterless distance. Optical amplifiers using Pr:doped glass for the 1310 nm has also been developed and would be potentially used for optical fiber systems and networks. Furthermore New types of optical amplifiers, including both lumped and distributed types, such as Raman, EDFAs and hybrid EDFA plus Raman offer very ultra-wide band DWDM optical communications.

It is therefore expected that optical channels over the entire spectrum between these wavelength windows would be used [1]. Ultra-high speed and ultra-wide bandwidth optical systems are required for maximizing the capacity of the optical transmission medium. It is thus desired to design and develop optical fibers that would have minimum non-zero and flattened dispersion over this ultra-broad spectral range.

Furthermore practical demonstrations of optical soliton fiber systems[2] have attracted interests to design of optical fibers which exhibit appropriate dispersion property to design dispersion-allocated[3] or dispersion-managed[4] optical fiber systems. The optical soliton transmission systems require accurate prediction of the dispersion factor of fibers in each section of transmission distance.

Advanced design of single mode fibers have been reviewed in numerous papers. Recently we have introduced key strategies for the design of optical fibers with modified dispersion characteristics [5]. This paper presents a new algorithm for finding in the saddle point of the waveguide dependent parameter that plays a major role in the waveguide dispersion factor for simplifying further the design of the dispersion profile of single mode fibers to ensure minimum dispersion. In this paper we present the following aspects of dispersion flattening in a non-uniform core optical fiber as follows. In the next section the background for modeling of dispersion

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flattened triple-clad fiber and an overview of the group velocity dispersion is also given with the view to focus to the development of the new algorithm for tailoring the dispersion characteristics of the triple-clad index profile fibers. Section 3 then gives the design guidelines for design of non-uniform core index profile to achieve significantly large waveguide dispersion to equalize that of the material dispersion. In particular the operating regions of the waveguide parameters are specified to obtain such equalization. Simulated results and discussions will be given in Sections 4 with a summary of the findings is given in Section 5.

DESIGN PARAMETERS AND EQUATIONS

A. The Group Velocity Dispersion (GVD)

The total dispersion factor, *D* in the unit of ps/(km-nm) of a single optical fiber is given by:

$$D = -\left(\frac{2\pi c}{\lambda^2}\right)\beta_2 \equiv D_M + D_W \tag{1}$$

where the parameter β_2 is well known as the GVD parameter; D_M and D_W are the material and waveguide dispersion factors respectively. Although these factors are well known we believe that a brief summary of the meaning of these factors is essential to present our new algorithm for designing the tripe clad optical fibers with dispersion flattened characteristics.

In case that the higher order dispersion is necessary the third order effect of the propagation parameter along the z-direction should be taken into account as

$$\beta_3 = \frac{d\beta_2}{d\omega} = \frac{d^3\beta}{d\omega^3} \tag{2}$$

The material dispersion in an optical fiber is due to the refractive index of silica, the material used for fiber fabrication, changes with the optical frequency. The refractive index *n(λ)* is approximated by the well known Sellmeier equation:

$$n^2(\lambda) = 1 + \sum_{j=1}^{M} \frac{B_j \lambda^2}{\left(\lambda^2 - \lambda_j^2\right)} \tag{3}$$

where λ_j is the resonance wavelength and B_j is the oscillator strength. Here *n* stands for n_1 or n_2 depending on whether the dispersive properties of the core or cladding are considered. These constants have been tabulated for several kinds of fibers in Table 1. The first three Sellmeier terms, i.e. B_1, B_2 a B_3, are used.

The first, second and third derivatives of the Sellmeier's equation can be easily obtained using symbolic calculation software packages, e.g. *Mathematica*. The derivatives of the refractive index as a function of wavelength can then be used to define the parametersβ, β_3 and the material dispersion factor, D_M as:

$$n(\lambda) = \sqrt{1 + \sum_{j=1}^{3} \frac{B_j \lambda^2}{\left(\lambda^2 - \lambda_j^2\right)}} \tag{4}$$

with the first derivative given by

$$\frac{dn(\lambda)}{d\lambda} = \frac{\sum_{j=1}^{3}\left\{\frac{2\lambda B_j}{\lambda^2 - \lambda_j^2}\left(1 - \frac{\lambda^2 B_j}{\left(\lambda^2 - \lambda_j^2\right)}\right)\right\}}{2\sqrt{1 + \sum_{j=1}^{3}\frac{\lambda^2 B_j}{\left(\lambda^2 - \lambda_j^2\right)}}} \tag{5}$$

the second derivative is given by

$$\frac{d^2 n(\lambda)}{d\lambda^2} = \frac{\sum_{j=1}^{3}\frac{2B_j}{\lambda^2 - \lambda_j^2}\left(1 - \frac{5\lambda^2}{\left(\lambda^2 - \lambda_j^2\right)} + \frac{4\lambda^4}{\left(\lambda^2 - \lambda_j^2\right)^2}\right)}{2\sqrt{1 + \sum_{j=1}^{3}\frac{\lambda^2 B_j}{\left(\lambda^2 - \lambda_j^2\right)}}} - \frac{\sum_{j=1}^{3}\frac{2\lambda B_j}{\lambda^2 - \lambda_j^2}\left(1 - \frac{\lambda^2}{\left(\lambda^2 - \lambda_j^2\right)}\right)}{4\left(1 + \sum_{j=1}^{3}\frac{\lambda^2 B_j}{\left(\lambda^2 - \lambda_j^2\right)}\right)^{\frac{3}{2}}} \tag{6}$$

and third derivative given by

$$\frac{d^3 n(\lambda)}{d\lambda^3} = \frac{3\sum_{j=1}^{3}\frac{2\lambda B_j}{\lambda^2 - \lambda_j^2}\left(1 - \frac{\lambda^2}{\left(\lambda^2 - \lambda_j^2\right)}\right)}{8\left(1 + \sum_{j=1}^{3}\frac{\lambda^2 B_j}{\left(\lambda^2 - \lambda_j^2\right)}\right)^{\frac{5}{2}}} + \frac{\sum_{j=1}^{3}\frac{24\lambda B_j}{\lambda^2 - \lambda_j^2}\left(-1 + \frac{3\lambda^2}{\left(\lambda^2 - \lambda_j^2\right)} - \frac{2\lambda^4}{\left(\lambda^2 - \lambda_j^2\right)^2}\right)}{2\sqrt{1 + \sum_{j=1}^{3}\frac{\lambda^2 B_j}{\left(\lambda^2 - \lambda_j^2\right)}}} - \frac{3\left\{\sum_{j=1}^{3}\frac{2B_j}{\lambda^2 - \lambda_j^2}\left(1 - \frac{5\lambda^2}{\left(\lambda^2 - \lambda_j^2\right)} + \frac{4\lambda^4}{\left(\lambda^2 - \lambda_j^2\right)^2}\right)\right\}\left\{\sum_{j=1}^{3}\frac{2\lambda B_j}{\lambda^2 - \lambda_j^2}\left(1 - \frac{\lambda^2}{\left(\lambda^2 - \lambda_j^2\right)}\right)\right\}}{4\left(1 + \sum_{j=1}^{3}\frac{\lambda^2 B_j}{\left(\lambda^2 - \lambda_j^2\right)}\right)^{\frac{3}{2}}} \tag{7}$$

The material dispersion factor, D_M is then given by:

$$D_M = -\frac{\lambda}{c}\left(\frac{d^2 n(\lambda)}{d\lambda^2}\right) \tag{8}$$

where c is the velocity of light in vacuum. In the spectral range of 1.25 μm-1.66 μm, it can also accurately approximate d to the first order by an empirical relation [6] given by:

$$D_M \approx 122\left(1 - \frac{\lambda_{ZD}}{\lambda}\right) \tag{9}$$

where λ_{ZD} is the zero material dispersion wavelength. For instance, λ_{ZD} = 1.276 μm is only for pure silica. λ_{ZD} can vary in the range 1.27 - 1.29 μm for optical fibers whose core and cladding are doped to vary the refractive index.

The effect of waveguide dispersion D_W on pulse spreading can be approximated in assuming that the refractive index of the material is independent of the wavelength. The contribution of D_W to the total dispersion parameter D, given by (1) depends on the V parameter of the fiber and is given by [6]:

$$D_W = -\left(\frac{n_1 - n_2}{\lambda_c}\right) V \frac{d^2(Vb)}{dV^2} \qquad (10)$$

where V is the normalized frequency and b is the normalized propagation constant which is defined according to different regions across the core and cladding layers. The normalized waveguide dispersion parameter $Vd^2(Vb)/dV^2$ depends strongly on V and plays a central role in the pulse spreading in single mode step-index fibers.

For doped silica fibers, the attenuation minima are in the 1300 nm and 1550 nm wavelength windows. Segmented-layer-index fibers (e.g. dispersion-flattened fibers) are used for high capacity and long distance optical transmission links because of its low total dispersion in that range. It is apparent that dispersion flattening in the wavelength region of the interest can be achieved only if a layer with a lower refractive index than that of the uniform cladding is introduced close to the core (i.e. depressed cladding) [5].

B. *The Dispersion Slope*

The dispersion slope is defined as

$$S = \frac{dD}{d\lambda}\ ps/nm^2km$$ or alternatively as [6, 15]

$$S = \left(2\pi c/\lambda^2\right)^2 \beta_3 + \left(4\pi c/\lambda\right)\beta_2$$

where

$$\beta_2 = \lambda^2 \frac{(1-\Delta)}{2\pi c^2}(\lambda(1+b(v)\delta)\frac{d^2 n}{d\lambda^2} + 2\lambda\Delta\frac{dn}{d\lambda}\frac{db(v)}{d\lambda} + \Delta\lambda n\frac{d^2}{d\lambda^2}$$

and

$$\beta_3 = \frac{(\lambda^2(1-\Delta))}{4\pi^2 c^3} 3\lambda^2(1+b(v)\Delta\frac{d^2 n}{d\lambda^2} + 3\Delta\lambda^3\frac{d^2 n}{d\lambda^2}\frac{db(v)}{d\lambda} + \ldots$$

$$+ (1+b(v)\Delta)\lambda^3\frac{d^3 n}{d\lambda^3} + 6\lambda^2\Delta\frac{dn}{d\lambda}\frac{db(v)}{d\lambda} + \ldots.$$

$$\ldots 3\Delta\lambda^3\frac{dn}{d\lambda}\frac{db(v)}{d\lambda^2} + 3\lambda^2\Delta n\frac{d^2 b(v)}{d\lambda^2} + \lambda^3 n\frac{d^3 b(v)}{d\lambda^3}$$

with

$$\frac{db(v)}{d\lambda} = 1.9920(\frac{2\pi}{\lambda})a1\sqrt{2\Delta}(1.1428 - \frac{0.9960}{V_{12}})(\frac{dn}{d\lambda}\Big/{V_{12}}^2)$$

$$\frac{d^2 b(v)}{d\lambda} = 1.9920(2\pi/\lambda)a1\sqrt{2\Delta}((0.9960/{V_{12}}^4)\frac{dn}{d\lambda}(2\pi/\lambda)a1\sqrt{2\Delta}(\frac{dn}{d\lambda})^2 + \ldots..$$

$$\ldots(1.1428 - 0.9960/V_{12})(\frac{d^2 n}{d\lambda^2}\Big/{V_{12}}^2 - (2\pi/\lambda)a1\sqrt{2\Delta}(\frac{dn}{d\lambda})^2/V_{12}^3)$$

$$\frac{d^3 b(v)}{d\lambda^3} = 1.984((2\pi/\lambda)a1\sqrt{2\Delta})^2(2\frac{dn}{d\lambda}\frac{d^2 n}{d\lambda^2}/V_{12}^4 - 4((2\pi/\lambda)a1\sqrt{2\Delta})(\frac{dn}{d\lambda})^3/V_{12}^5)$$

$$\frac{dn}{d\lambda} = -(\lambda/n)n_a$$

where

$$n_a = b(i)\ \lambda(i)^2/(\lambda^2 - \lambda(i)^2)^2$$

$$\frac{d^2 n}{d\lambda^2} = (A/(2\sqrt{(1+B)})) - (c/4\sqrt{(1+B)})$$

$$\frac{d^3 n}{d\lambda^3} = (D/(8^{1.5}\sqrt{(1+E)}) + (F/\left(2\sqrt{(1+E}\right)) - 3GH/\left(4(1+E)^{1.5}\right)$$

in which the coefficients A-H are given by

$$D = 2\lambda b(i)\left(1 - \lambda^2/\lambda_1\right)/\lambda_1 \text{ with } \lambda_1 = \lambda^2 - \lambda(i)^2$$

$$E = \lambda^2 b(i)/\lambda_1$$

$$F = \left(24\lambda\ b(i)\left(-1 + 3\lambda^2/\lambda_1\right) - 2\lambda^4/\lambda_1^2\right)/\lambda_1$$

$$G = \left(2b(i)\left(1 - 5\lambda^2/\lambda_1 + 4\lambda^4/\lambda_1^2\right)\right)/\lambda_1$$

$$H = \left(2\lambda b(i)\left(1 - \lambda^2/\lambda_1\right)\right)/\lambda_1$$

$$A = \left(2b(i)\left(1 - 5\lambda^2/\lambda_1 + 4\lambda^4/\lambda_1^2\right)\right)/\lambda_1$$

$$B = \left(\lambda^2 b(i)\right)/\lambda_1$$

$$C = \left(2\lambda b(i)\left(1 - \lambda^2/\lambda_1\right)\right)/\lambda_1$$

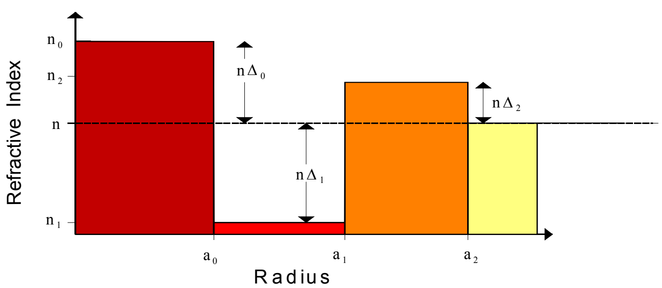
C. *Triple-Clad Profile*

In this section the relationship between the fiber geometrical structure, the index profile, its total dispersion, the fundamental mode spot size are examined. The sensitivity of the total dispersion of fibers due to changes in the structural parameters (a_0, a_1 a_2, n_0, n_1, n_2, n_3, n) are shown in Figure 1. Ten different fiber material types are used as core materials and/or cladding .The maximum dispersion not higher than 3 ps/(nm.km) is set as an example in this work, over the wavelength range of 1300 to 1580nm and even longer. These materials and their Sellmeir's coefficients are tabulated in Table 1. They are coded Types 1-10 numerically or alphabetically A to H.

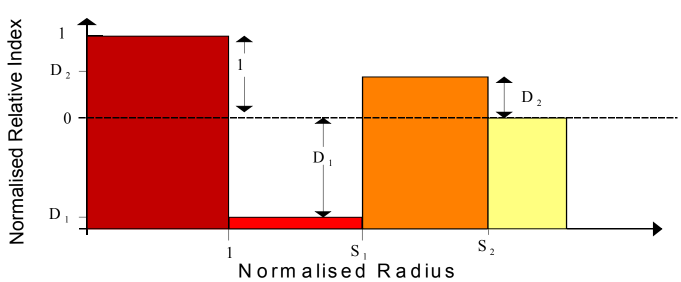
The waveguide dispersion plays an important role in '*shaping*' the total dispersion curve. As there are three layers of cladding (Figure 1), it is expected to obtain three waveguide dispersion factors for the three cladding regions, namely D_{W1}, D_{W2} and D_{W3}. Hence, the effects of each structural parameter are examined to satisfy specific dispersion characteristics. Eq.(10) clearly shows that the waveguide dispersion depends on the waveguide dispersion parameter, $Vd^2(Vb)/dV^2$.

type	Doping Conc.:	SiO_2 :	B1	B2	B3	λ1	λ2	λ3
A **(1)**	0%	100%	0.6961663	0.4079426	0.8974794	0.0684043	0.1162414	9.896161
B **(2)**	3.1%	96.9%	0.7028554	0.4146307	0.8974540	0.0727723	0.1143085	9.896161
C **(3)**	5.8%	94.2%	0.7088876	0.4206803	0.8956551	0.0609053	0.1254514	9.896162
D **(4)**	7.9%	92.1%	0.7136824	0.4254807	0.8964226	0.0617167	0.1270814	9.896161
E **(5)**	0%	pure	0.696750	0.408218	0.890815	0.069066	0.115662	9.900559
F **(6)**	13.5%	86.5%	0.711040	0.408218	0.704048	0.064270	0.129408	9.425478
G **(7)**	9.1%	90.9%	0.695790	0.452497	0.712513	0.061568	0.119921	8.656641
H **(8)**	13.3%	86.7%	0.690618	0.401996	0.898817	0.061900	0.123662	9.098960
I **(9)**	1%	99%	0.691116	0.399166	0.890423	0.068227	0.116460	9.993707
J **10**	48.7%	51.3%	0.796468	0.497614	0.358924	0.094359	0.093386	5.999652

Table 1: Sellmeier's coefficients for silica based material and doping concentration for the design.



(b)



(b)

Figure 1 Refractive index profile of a triple-clad fiber indicating: (a) the unnormalized index profile, and (b) the normalized profile

Numerous attempts to approximate this equation to represent this curve. Thus, the modeling of this curve is to be determined prior to designing the fiber.

D. Profile Construction

The refractive index profile of the triple-clad step-index fiber is shown schematically in Figure 1(a). Figure 1(b) shows the unnormalized profile and Figure 1(c) shows the normalized profile where a_i - the ith outer radius, n_i - the refractive index of the *i-th* layer and *n* - the refractive index of the uniform cladding. The refractive index of the *i*-th layer relative to that of the uniform cladding is thus given by [9,10]:

$$\Delta_i = \frac{n_i - n}{n} \qquad (11)$$

The normalized outer radius is defined as

$$S_i = \frac{a_i}{a_0} \qquad (12)$$

The normalized relative index of the *i-th* layer is defined as

$$D_i = \frac{\Delta_i}{\Delta_0} \qquad (13)$$

with $S_0=1$ and $D_0=1$. It is convenient to express the degrees of freedom in terms of the structural parameters a_0, S_1, S_2, n_0, D_1, D_2 and *n*.

A uniform cladding of pure silica (Fiber Type A) is chosen for analysis in this paper and the Sellmeier expansion is used to calculate the refractive index and its derivatives with wavelength. Ten different material types (type A to type J) of the silica base and different doping concentration of dopants as tabulated in Table 1 are also used in the analysis as the core materials of the single-mode triple-clad optical fibers in order tailoring the total dispersion factor meeting the requirement of maximum total dispersion not larger than a certain limit of dispersion. In this paper we set this limit to 3 ps/(nm.km) in the operating wavelength range of 1300 nm to 1580 nm. This limit can be varied if desired. However in order to place minimum difficulty for manufacturing the fiber the limit of 3 ps/(nm.Km) is sufficient for large bandwidth-length product.

A simulation program using **MATLAB®** for triple-clad dispersion-flattened single mode fibers is developed in which ten different material types (type A to type J) of single-mode triple-clad optical fibers are used in the design to meet specified ceiling of maximum total dispersion in the operating wavelength range of 1300 nm to 1580 nm. The V-dependent parameter representing the waveguide dispersion parameters D_W can be determined as there is no exact expression to represent the curve. Seven fiber parameters namely core radius (a_0), first cladding radius (a_1), second cladding radius (a_2), core index (n_0), first cladding index (n_1), second cladding index (n_2) and outer cladding index (n) that constitute seven degrees of freedom in designing these fibers.

The effects of these parameters on total dispersion are studied and analyzed. Furthermore the effects of doping concentration on total dispersion are briefly discussed.

E. Waveguide Guiding Parameters of TheTriple-Clad Profile Fiber

The transverse propagation constants of the guided optical fields ***u/a*** and ***v/a*** in the core and cladding (evanescent field) regions respectively are given for the core and the fist and second cladding layers (with subscripts 1, 2 and 3 respectively) of the triple-clad index profile fibers as

$$u_0 = a_0\sqrt{k^2 n_0^{\ 2} - \beta_0^{\ 2}} \tag{14a}$$

$$u_1 = a_1\sqrt{k^2 n_1^{\ 2} - \beta_1^{\ 2}} \tag{14b}$$

$$u_2 = a_2\sqrt{k^2 n_2^{\ 2} - \beta_2^{\ 2}} \tag{14c}$$

$$v_0 = a_0\sqrt{\beta_0^{\ 2} - k^2 n^2} \tag{15a}$$

$$v_1 = a_1\sqrt{\beta_1^{\ 2} - k^2 n^2} \tag{15b}$$

$$v_2 = a_2\sqrt{\beta_2^{\ 2} - k^2 n^2} \tag{15c}$$

where β_0, β_1 and β_3 are the propagation constants in the z-direction of the guided waves in the core and first and second cladding layers of the triple-clad fiber which are given by

$$\beta_0 = \sqrt{k^2(b_0(n_0^{\ 2} - n^2) + n^2)} \tag{16a}$$

$$\beta_1 = \sqrt{k^2(b_1(n_1^{\ 2} - n^2) + n^2)} \tag{17b}$$

$$\beta_2 = \sqrt{k^2(b_2(n_2^{\ 2} - n^2) + n^2)} \tag{17c}$$

Thus, the normalized frequencies for all layers can be expressed as

$$V_0 = a_0 k\sqrt{n_0^{\ 2} - n^2} \tag{18a}$$

$$V_1 = a_1 k\sqrt{\left|n_1^{\ 2} - n^2\right|} \tag{18b}$$

$$V_2 = a_2 k\sqrt{n_2^{\ 2} - n^2} \tag{18c}$$

defined as

$$V_{eff} = ka_0\sqrt{2n\left((n_0 - n_1) + (n_1 - n_2) + (n_2 - n)\right)} \tag{20}$$

The spot size r_0 can be found both analytically and empirically as [6, 7]:

$$\mathrm{r}_0 = \sqrt{\frac{\mathrm{a}_0^2}{\ln \mathrm{V}_{\mathrm{eff}}^2}} \tag{21}$$

The spot size is chosen so that there is a non-zero minimum dispersion can be obtained and satisfies the requirement for maximum effective area so as to maximize the nonlinear threshold power.. Furthermore with the Gaussian approximation the transverse intensity *I(r)* of the fundamental mode is given by:

$$I(r) \cong \exp\left(\frac{-1}{2}\left(\frac{r}{r_0}\right)^2\right) \tag{22}$$

The waveguide dispersion factors for triple-clad are the extension of equation (10)and are given by:

$$D_{W0} = -\left(\frac{n_0 - n_1}{\lambda c}\right)V_0\frac{d^2(V_0 b)}{dV_0^{\ 2}} \tag{23a}$$

$$D_{W1} = -\left(\frac{n_1 - n_2}{\lambda c}\right)V_1\frac{d^2(V_1 b)}{dV_1^{\ 2}} \tag{23b}$$

$$D_{W2} = -\left(\frac{n_2 - n}{\lambda c}\right)V_2\frac{d^2(V_2 b)}{dV_2^{\ 2}} \tag{23c}$$

where the normalized waveguide dispersion factor is $Vd^2(Vb)/dV^2$ *defined with appropriate parameters V for different cladding layers*. For triple-clad fiber we have the following three normalized waveguide dispersion parameters

$$\frac{V_0 d^2(V_0 b)}{dV_0^2} = 2\left(\frac{u_0}{V_0}\right)^2\left\{K_0(1-2K_0) + \frac{2}{v_0}\left(v_0^2 + u_0^2 K_0\right)\sqrt{K_0}\left(K_0 + \frac{1}{v_0}\sqrt{K_0} - 1\right)\right\} \tag{24a}$$

$$\frac{V_1 d^2(V_1 b)}{dV_1^2} = 2\left(\frac{u_1}{V_1}\right)^2\left\{K_1(1-2K_1) + \frac{2}{v_1}\left(v_1^2 + u_1^2 K_1\right)\sqrt{K_1}\left(K_1 + \frac{1}{v_1}\sqrt{K_1} - 1\right)\right\} \tag{24b}$$

$$\frac{V_2 d^2(V_2 b)}{dV_2^2} = 2\left(\frac{u_2}{V_2}\right)^2\left\{K_2(1-2K_2) + \frac{2}{v_2}\left(v_2^2 + u_2^2 K_2\right)\sqrt{K_2}\left(K_2 + \frac{1}{v_2}\sqrt{K_2} - 1\right)\right\} \tag{24c}$$

with

$$K_0 = \frac{BESSELK_1(v_0)}{BESSELK_0(v_0)} \tag{25a}$$

$$K_1 = \frac{BESSELK_1(v_1)}{BESSELK_0(v_1)} \tag{25b}$$

$$K_2 = \frac{BESSELK_1(v_2)}{BESSELK_0(v_2)} \tag{25c}$$

where $BESSELK_i$ are the *i-th* order modified Bessel functions. Finally, it is straightforward to find the total dispersion of a triple-clad optical fiber that is given by:

$$D_{TOT} = D_M + D_{W0} + D_{W1} + D_{W2} \quad (26)$$

F. Dispersion compensation

The design of fibre design for 40 Gb/s for the C, L and S band is the focus of this paper. This section is divided into two main parts.

The first part deals with the design of DFF for C-Band and L-Bands. The concept of a DFF has been investigated in the late 1970's for single channel transmission in order to ensure that the transmission is loss limited rather than dispersion limited and many published works can be referred to Refs [15-22]. In Ref.[16] a thorough investigation has been carried out for the doubly clad DFF with in-depth calculations on cut-off properties and index profile influences. Practical results in this paper were being compared in this works. In [17] mathematical equation like Bessel functions etc are used for estimating $V(d^2(VB)/dV^2$.

The idea of DCF had also been investigated since the early seventies and then extensively accelerated after the advent of optical amplifiers in the 1990's as the transmission system could no longer be loss limited but dispersion limited.. In [18] extensive mathematical concepts of DCF were presented. Though the Refractive Index Profile (RIP) is not an ideal step-index type,. The design principles for DCF have been well described. In [19] the concept of figure of merit is used. This figure of merit is defined as the ratio of the fiber dispersion factor to attenuation and Ref[18] investigates how dispersion, loss and effective area of the DCF interplay to determine the performance of a dispersion-managed optical transmission system. In [20], the concept of figure of merit is further studied. In [21] an optimal design for DCF and its fabrication are given. This paper deals with a graded index profile rather than a step-index one. The Dispersion Slope Compensation Ratio (DSCR) is uemployed which is simply the ratio of dispersion slope of DCF to the Dispersion factor of the DCF divided by ratio of the dispersion slope of the DFF to the Dispersion of DFF as

$$DSCR = S_{DCF}/D_{DCF}.\ D_{DFF}/\ S_{DFF} \quad (27)$$

This concept is used in [16] and a term 'Kappa" is coined instead for DSCR. Currently many manufacturers specify this value of Kappa for their DCF modules.

All the above references use *'triple clad optical fiber'* for the design of both DFF and DCF.

APPROXIMATION OF WAVEGUIDE DISPERSION PARAMETER CURVES

The three $Vd^2(Vb)/dV^2$ curves expressing (24a - 24c) are the exact solutions for the second-half of the complete curve shown in Figure 2. However, to the best of our knowledge neither simple approximation nor exact representation of $Vd^2(Vb)/dV^2$ curve are available in any published works. Most published works [9, 10] and the algorithm developed in Ref. [13] are far too complicated to analyze and for clarity, particularly at the design inception stage. Therefore, we develop, in this section, a simple *algorithm* to predict the behavior of $Vd^2(Vb)/dV^2$ curve in the following steps.

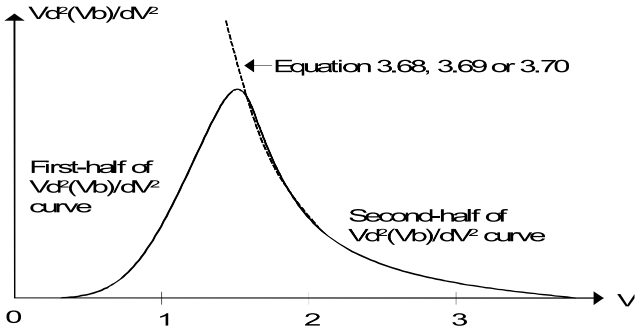


Figure 2 $Vd^2(Vb)/dV^2$ complete curve, dotted line is obtained from (24a), (24b) and (24c).

STEP 1

The exact $Vd^2(Vb)/dV^2$ curves developed in (24a)-(24c) are used for the second-half (after the maximum peak) of the curves. The peaks of the respective curves can be accurately determined. By inspecting a number of family $Vd^2(Vb)/dV^2$ curves reported in [13] and [5] are plotted as shown in Figure 3, and it is surprising that we can predict the peaks by crossing the curves by a cubic equation given by a simple equation,

$$\left(V\frac{d^2(Vb)}{dV^2}\right) = V^3 \quad (28)$$

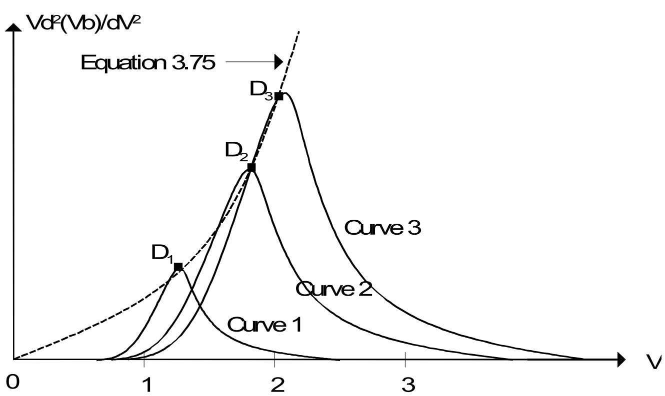


Figure 3 $Vd^2(Vb)/dV^2$ family curves

Thus, the intercepting point, point **D**(Dx,Dy) (Figure 4) is the corresponding peak of one of the curves. A correction factor can be used to modify (27) if required, mainly the constant of the cubic equation. Higher order polynomial is found to be unnecessary in this case.

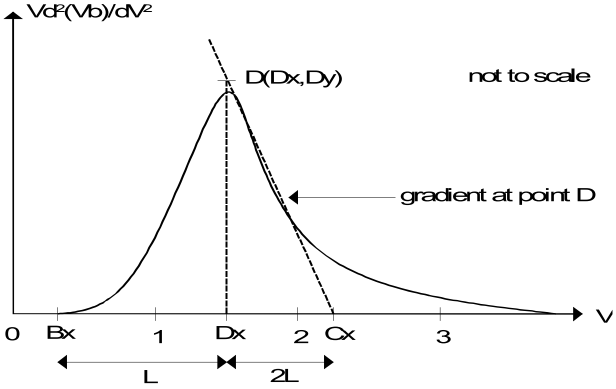


Figure 4 The variation of the waveguide parameter $Vd^2(Vb)/dV^2$ *as a function of the V-parameter*. The behavior of the right half of the curve is estimated with a number of predicted points.

STEP 2

From Figure 4 and referring to point **D**(Dx,Dy), we could find the gradient at that point and hence the point Cx shown in the same figure by using (27) :

$$Cx = Dx - \frac{Dy}{\left(\frac{d}{dV} \left(\frac{Vd^2(Vb)}{dV^2} \right) \right)_{at(Dx,Dy)}} \quad (29)$$

STEP 3

Having found point **C**(Cx,0) we could predict point **B**(Bx,0) i.e. the cutoff point for $Vd^2(Vb)/dV^2$ curve by using (28).

$$Bx = Dx - \frac{1}{2}(Cx - Dx) \quad (29)$$

STEP 4

Now considering the curve from point **B** to point **D**, we have to introduce additional points in order to obtain the desired shape. Likewise, a few points are selected to represent the curve in the right-half of the $Vd^2(Vb)/dV^2$ curve. All together, we have selected ten points to represent the $Vd^2(Vb)/dV^2$ curve. Having obtained the significant points, our next task is to interpolate all the points to form a smooth curve. *Spline interpolation* method has been adopted for this purpose.

STEP 5

As we are using the $Vd^2(Vb)/dV^2$ curve to find the waveguide dispersions defined in (24a) -(24c) the curves as shown in Figure 5 can be represented by a general mathematical expression as a function of wavelength. Thus, a polynomial of *9-th* order given by (29) has been chosen for this purpose. For single-mode, the normalized frequency is given by,

$$V_i = 2.405 \left(\frac{\lambda_{ci}}{\lambda} \right) \quad (30)$$

where λ_{ci} is the cutoff wavelength of i-th cladding region.

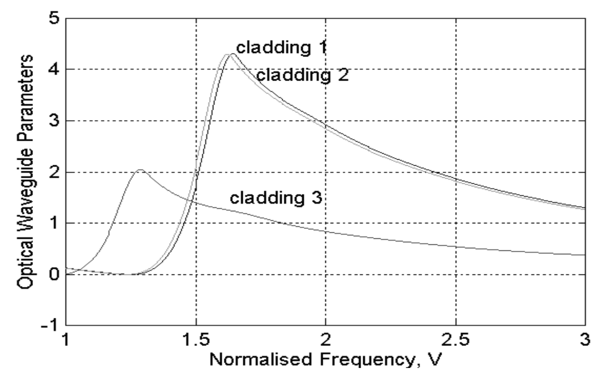


Figure 5 The optical waveguide parameter curves for optical fibers with three cladding types.

Hence, the *9-th* order of $Vd^2(Vb)/dV^2$ polynomial can be approximated by,

$$V\frac{d^2(Vb)}{dV^2} = P_0 + P_1\left(\frac{2.405\lambda_c}{\lambda}\right) + P_2\left(\frac{2.405\lambda_c}{\lambda}\right)^2 + P_3\left(\frac{2.405\lambda_c}{\lambda}\right)^3 + \ldots + P_9\left(\frac{2.405\lambda_c}{\lambda}\right)^9 \quad (31)$$

or

$$V\frac{d^2(Vb)}{dV^2} = \sum_{m=0}^{9} P_m \left(\frac{2.405\lambda_c}{\lambda}\right)^m \quad (32)$$

where $P_0, P_1, P_2, ..., P_9$ are the polynomial constants which have been obtained by using the *polyfit* function in **MATLAB** ®[12].

The design presented above involves seven degrees of freedom. By analyzing the effect of each parameter we would be able to predict the changes of the dispersion factor and identify the main factors that would play a major role in the tailoring of this factor. Ten different types of materials as listed in Table 1 have been used in the core/cladding regions to design dispersion flattened fibers in order to meet the requirement which should not be zero but have some finite dispersion so that the four mixing effects do not occur between adjacent wavelength channels.

Material types A, B, C, D, E, F, G, I and J can be used as either core or cladding materials of optical fibers that would satisfy the dispersion-flattening limit requirement. Material type H has the total dispersion of about 9 ps/(nm-km) in the range 1300-1580 nm. Analyzing all the total dispersion curves leads to a conclusion that the fiber with material type J gives the best performance in dispersion flattening as a total dispersion less than 3 ps/(nm-km) from 1280 nm to 1620 nm can be achieved.

There is a maximum of three zero dispersion points. The first and second zero dispersion points are approximately located in the two fiber windows (1300 nm and 1550 nm). It is well known that from the silica loss any wavelength above 1700 nm would cause severe attenuation loss in transmission. On average, the third zero-dispersion point is above 1700 nm. Thus, we are not interested in it or unless we could design it as such that this point lies within the fiber windows.

G. Effect of Core and Cladding Radius on the Total Dispersion

Figures 6, 7, 8 and 9 show various curves of core/cladding radius against total dispersion. We observe the following effects of each core/cladding radius on the dispersion characteristics:

(i) As the core radius, a_0, is increased the total dispersion curve is shifted upwards at the same time the second zero dispersion point is shifted to the higher wavelength. Meanwhile, the first zero dispersion point remains unchanged and the third zero dispersion point gradually shifted to the lower wavelength. By simulating and analyzing the behavior of the dispersion curves, we obtain the maximum sensitivity of changes in a_0 to total dispersion in the fiber windows region is about 88.88 ps/(nm-km-mm).

(ii) As the first cladding radius, a_1, is reduced the total dispersion curve is shifted upwards. The maximum sensitivity of changes in a_1 to total dispersion in the fiber windows region of 64.68 ps/(nm-km-mm) is obtained.

(iii) As the second cladding radius is reduced, a_2, the total dispersion curve is shifted upwards, but the first zero dispersion point are shifted to the lower wavelength, a maximum sensitivity of changes in a_2 to total dispersion in the fiber windows region of 0.99 ps/(nm-km-mm) is obtained.

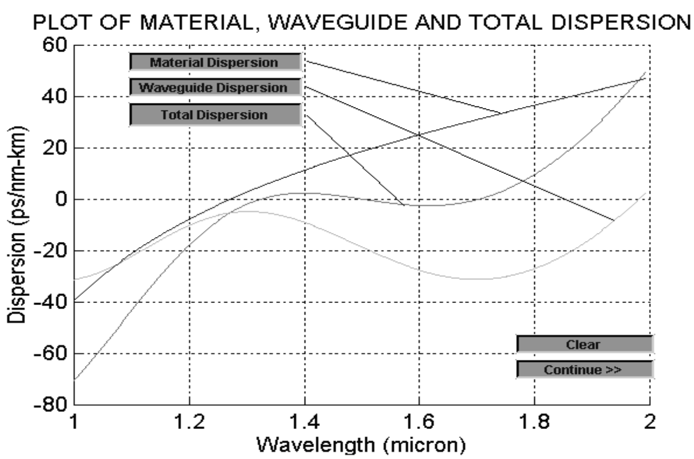


Figure 6 Material, waveguide and total dispersion of 'type A' as the core material of a triple clad profile as a parameter.

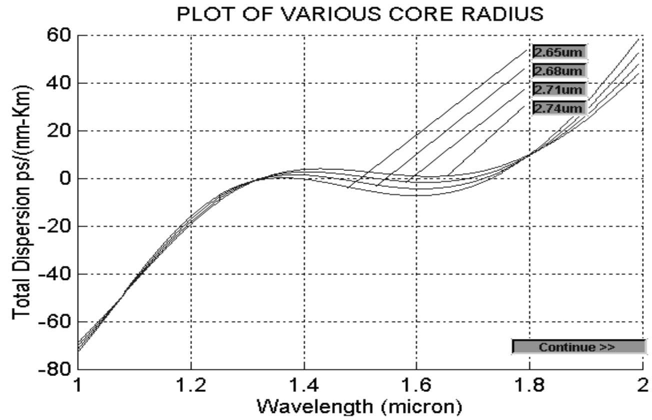


Figure 7 Spectral distribution of the total dispersion factor with the core radius of the triple clad optical fiber as a parameter

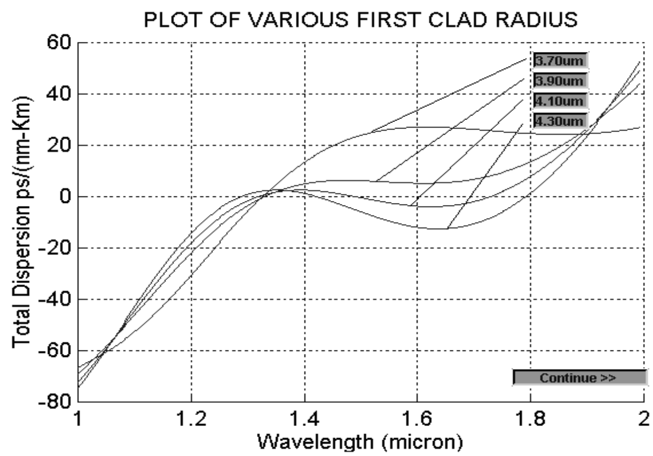


Figure 8 Spectral distribution of the total dispersion factor with the first cladding radius of the triple clad optical fiber as a parameter.

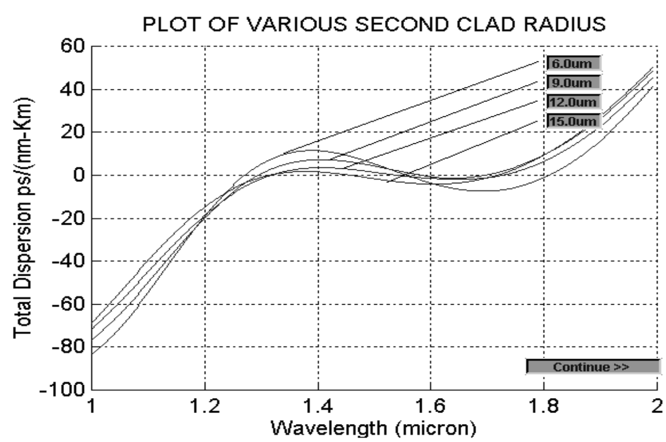


Figure 9 Spectral distribution of the total dispersion factor with the second clad radius of the triple clad optical fiber as a parameter

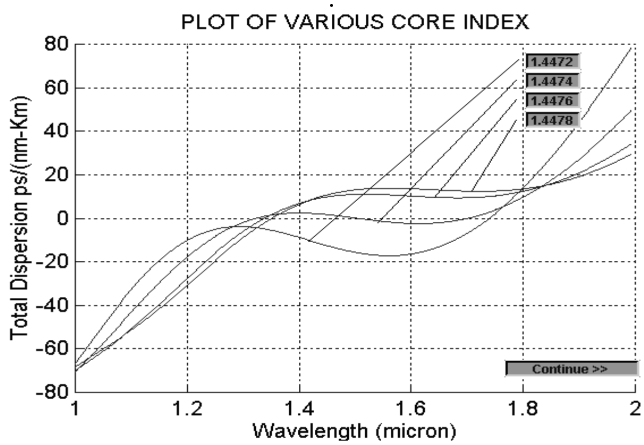


Figure 10 The Spectral distribution of the total dispersion factor of triple-clad fibers with the core refractive index of the triple clad optical fiber as a parameter.

From the above results, we can conclude that the change in core radius, a_0 is very sensitive to the total dispersion factor with a sensitivity of 88.88 unit dispersion per unit μm as compared to that of the outer radius of the second layer a_2. Thus, the selection of a_0 is very critical to achieve a specified dispersion factor for the triple-clad fiber, and hence the manufacturing tolerance or the deformation of the fiber core radius during installation. Extreme care should be carried out especially the bending curvature and pressure applied during installation. The sensitivity of each core radius is compared with respect to that of the second cladding layer as shown in Table 2. Thus the manufacturing tolerance of the fiber core radius must be controlled accurately as compared to those of the cladding layers.

	a_0	A_1	a_2
Normalised			
Sensitivity	89.7	65.3	1

Table 2 Normalised sensitivity comparison of core, first and second cladding radius

H. Effect of Refractive Indices of the cladding layers on Total Dispersion

Referring to Figures 10, 11, 12 and 13, various curves of core / cladding refractive indices versus the fibre total dispersion are plotted. These curves show the following effects:

(i) As the core refractive index, n_0, is reduced, the total dispersion curve is shifted upwards. Several curves are obtained and the maximum sensitivity of changes in n_0 to total dispersion in the fiber windows region is 50,000 ps/(nm-km) per unit relative refractive index is observed..

(ii) When the first cladding refractive index, n_1, is increased the total dispersion curve is shifted upwards and the first zero dispersion wavelength is moved towards higher wavelength region. We have obtain the maximum sensitivity of changes in n_1 to total dispersion in the fiber windows region is 59,200 ps/(nm-km) per unit refractive index.

(iii) As the second cladding refractive index, n_2, is decreased the total dispersion curve is shifted upwards but the first zero dispersion point is shifted to the lower wavelength. Meanwhile, the second zero dispersion point almost remains unchanged. Further simulation results that the maximum sensitivity of changes in n_1 to total dispersion in the fiber windows region is 6666 ps/(nm-km) per unit refractive index.

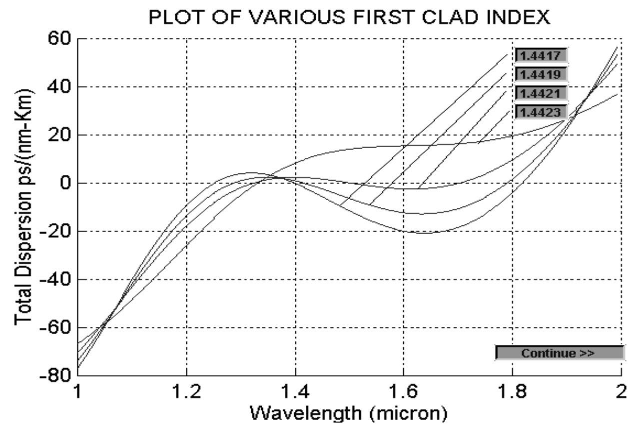


Figure 11 Dispersion factor versus wavelength with the first cladding refractive index of triple clad profile as a parameter.

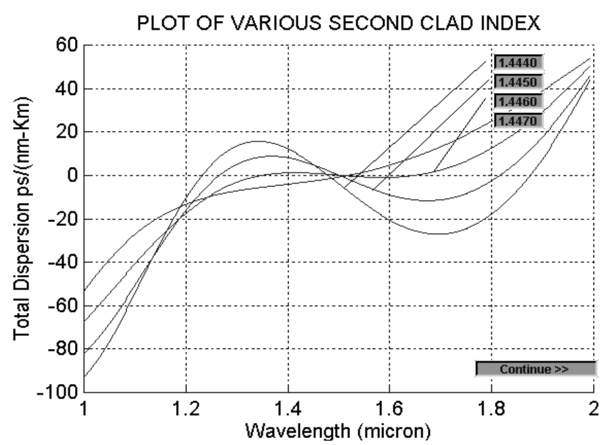


Figure 12 Spectral distribution of the total dispersion factor with the second cladding refractive index of the triple clad profile as a parameter

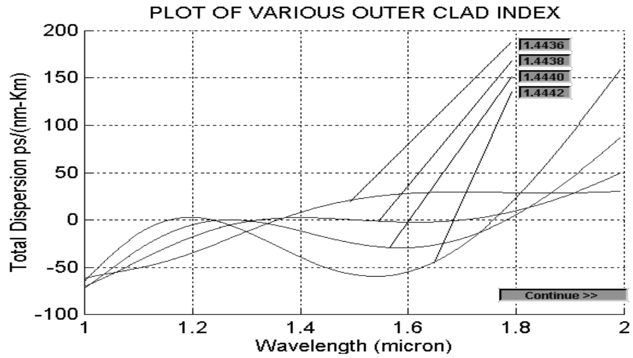


Figure 13 The spectral distribution of the total dispersion factor varies with the outer cladding refractive index of the triple clad profile as a parameter

(iv) As the outer cladding refractive index, *n*, is decreased the total dispersion curve is shifted upwards but the first and second zero dispersion points are shifted to longer spectral region. We obtain a maximum sensitivity of changes in n_1 to total dispersion in the fiber windows region is 142,850 ps/(nm-km) per unit refractive index change 10^{-4}.

We thus conclude that changes in outer refractive index, *n* is sensitive to the total dispersion (i.e. 142,850 unit dispersion per unit refractive index) compared to the n_2. Thus, selecting *n* is very critical to the triple-clad step-index optical fiber. The normalized sensitivity of the refractive indices of the core and the cladding layers with respect to the refractive index of the third cladding layer n_2 is shown in Table 3. This layer is chosen for normalization due to its closeness to the cladding outer most cladding layer. It shows clearly that the outer most cladding layer is the most sensitive as indicated and the degree of sensitivity so that designer can have a clear choice of the geometrical parameters of the fiber.

	n_0	n_1	N_2	N
Normalized Sensitivity	7.50	8.88	1.00	21.43

Table 3 Normalized sensitivity comparison of core, first, second and outer refractive index

I. Effect of Doping Concentration on the Total Dispersion

Figure 14 indicates that increasing doping concentration would shift the total dispersion curve down slightly. The change is quite small and an estimate change of 0.5 unit dispersion per unit concentration. Thus the doping concentration in the core region does not play a major role in the flattening of the total dispersion curve. The doping concentration would thus be the last factor to consider in the design of the triple-clad step-index fibers. This factor should be considered for its contribution to the attenuation of optical signals.

DESIGN ALGORITHM FOR DFF:

Step 1: Initially the material dispersion is calculated based on the materials tabled in Table 1. Figure 14 shows typical curve for material dispersion against wavelength:

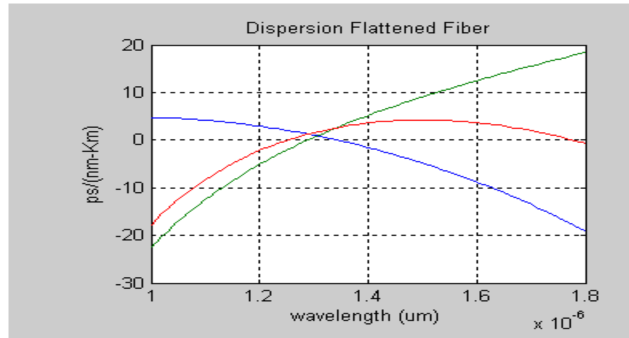


Figure 14: Spectral variations of the material dispersion (green), waveguide dispersion (blue) and total dispersion (red). The fibre profile is: Core Type= Material B (2), Core Radius = 3.8625μm, Index difference = 0.98%.

Step 2: The criteria for the design of dispersion -"free" fibers is to compensate for this material dispersion by the waveguide dispersion or effectively the group delays of the red shift and blue shifts are in opposite directions. Thus the waveguide dispersion is calculated for various cladding layers, which can balance the material dispersion for the range of 1.3 to 1.7 μm. To calculate waveguide dispersion the parameter $V(d^2(Vb)/dV^2)$ is estimated so that the chirp of the blue-shift would be in the opposite direction of that exerts on the red shift chirping effect due to the material refractive index over the ultra-wide spectral range. This is illustrated in Figure 14.

Step 3: The waveguide dispersion is added to the material dispersion and thus the total dispersion for the range of 1.3 to 1.7 μm. It is observed that very low non- zero value obtained to avoid the four wave mixing effects. The total dispersion curve can be shown in Figure 15.

DESIGN PROCEDURES FOR DISPERSION COMPENSATING FIBER:

Similarly to the design of DFF, the algorithm used in designing DCF is performed except there is only a difference in that DCF is a section of fibre deployed in the link that should compensate the GVD of various components in the fibre. The group velocities of say a RED SHIFT part of the signal are in opposite with those of BLUE SHIFT section. When the signal travels through long stretch of Dispersion Flattened fibre then these signals lag in distance due to various velocity of propagation. The DCF compensates this anomaly. The basic equation required is

$$|D_{dff}L_{dff}| = |D_{dcf}L_{dcf}|,$$

i.e. the dispersion allowance is maintained over several spans of the link.

J. Design Steps:

Step 1: Select the material type for the DCF. Then change the radius of the fibre core to around 1 μm and check the dispersion curve.

Step 2: Change the index slider so that the Dispersion of the fibre becomes very negative. Check the window such that $|D_{dff} L_{dff}| = |D_{dcf} L_{dcf}|$ as shown in Figure 15 and Figure 17.

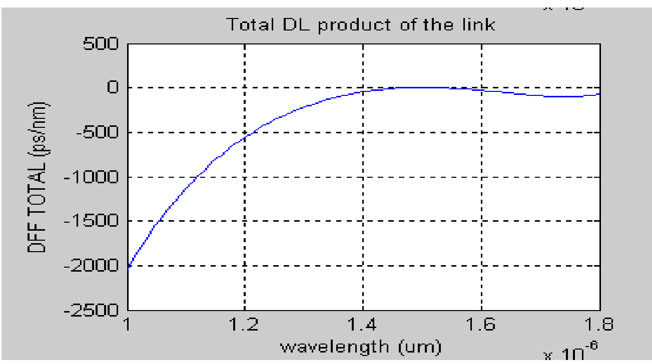


Figure 15 The dispersion-length product over ultra-wide spectral range

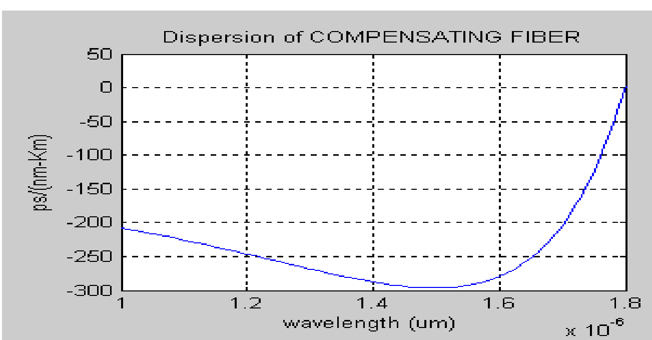


Figure 16: Dispersion factor of the DCF with a profile of: Core Type= Material G (7), Radius = 1.59938μm Relative index difference = 1.57 % and DCF length = 1.39241 Km.

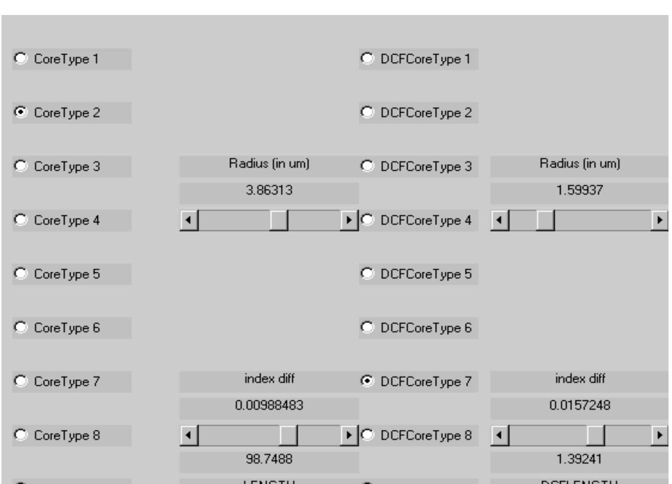


Figure 17 Various combinations of radius, type of material, RI profile and length of the fibre deduced in the design that satisfies the dispersion flattening. Corresponding dispersion factors and slopes are shown in Figures 18 and 21

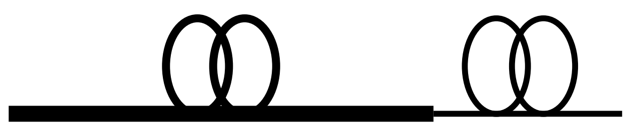
CASE STUDIES

The spectral dispersion characteristics of the designed fibers can be matched with any specific dispersion characteristics for both the DFF and DCF. This section presents two case studies of typical designs of the dispersion flattened and compensated fibers. It is imperative to justify the results with the values obtained for all the parameters used such as the number of guided modes, the core and cladding layer radii, relative index difference, spot size etc. The selection of the parameters can be inserted in windows provided in Figure 17. This allows fine adjustment of the parameters.

The results are presented in Figures 20 and 22 with windows numbered from left to right and top to bottom for the design cases presented in the next sections.

K. Design case 1:

In this case the Core material is of Type B and results are obtained for the DFF and DCF as shown in Figure 18 for transmission of at least 40 Gb/s over several hundred kms.



DFF (TYPE 2 Core) (DCF Type 7 Core)

Figure 18 Dispersion managed optical fibre span

The following results are obtained and illustrated with the windows numbered from left to right and top to bottom in Figure 19 as follows:

• **Window 1:** This is the most important window of the plot as it indicates the dispersion of the optical fibre used for communications systems. We design a dispersion-flattened fibre for a range from S band to L bands and hence it is important to notice the changes in this window so that the requirements are met. This window can be called as the GUIDING WINDOW for our design. The Dispersion Flattened Fibre (DFF) characteristics are satisfied with a low dispersion range of 0 ps/nm-km to 3 ps/nm-km in the range 1.3 nm to 1.6 nm.

• **Window 2:** The dispersion of the dispersion compensated fibre is designed such that the Kappa Value approaches unity.

- **Window 3:** The dispersion slope of both the DFF and DCF are plotted where the blue line indicates the slope of DFF and green line indicates the slope of DCF.

- **Window 4:** This window shows the plot of "V (d^2(VB)/dV2)" versus "normalized frequency". The blue line indicates the characteristics of V(d^2(Vb)/dV2) versus V_{12} while the green line indicates the characteristics of V(d^2(Vb)/dV2) versus V_{13}

- **Window 5:** The refractive index of the fibre is shown in this window. The blue line shows the RIP of Core which varies from 1.4525 @ 1.3 µm to 1.4475 @1.6 µm. The RI of first cladding is the green line which varies from 1.4425 @ 1.3 µm to 1.4375 @1.6µm. Finally the red line indicates the RI of outer cladding which varies from 1.448 @1.3 µm to 1.4475 @ 1.6 µm.

- **Window 6:** shows the spot-size of the DFF as a function of the operating wavelength. Reasonable spot size is obtained as compared with the standard single mode fibre G.652 or G.655.

- **Window 7** shows the rise time budget of the fibre. The green line is the theoretical value, which is taken as **0.5/40 ns**. The reason being that we are taking NRZ format, which is taken theoretically as **0.75/40 ns**. But taking practical considerations the value is decreased to **0.5/40 ns**.

- **Window 8:** gives the KAPPA value which meets the criteria – Kappa value reaches unity.

- **Window 9:** gives the DL product of the link, which is very close to Zero hence efficient transmission for ultra-long reach is expected.

L. Design case 2:

In this case the Core is made of Type E material for the DFF and DCF as shown in Figure 19.

DFF (TYPE 5 Core) (DCF Type 7 Core)

Figure 19 Dispersion-managed fibre span with different core materials

Figures 20 illustrates the simulated and designed results as follows:

- **Window 1:** The DFF characteristics are met properly with a non-zero and low dispersion range lower than few ps/nm-km over the spectral range 1300 nm to 1600 nm.

- **Window 2:** The total dispersion factor of the DCF is designed such that the Kappa Value can reach unity.

- **Window 3:** The dispersion slopes of both the DFF and DCF are plotted where the blue line indicates the slope of DFF and green line for DCF.

- **Window 4:** shows the plot of "V(d^2(Vb)/dV2)" versus "normalized frequency". The blue line indicates the characteristics of V(d^2(Vb)/dV2) versus V_{12} while the green for V(d^2(Vb)/dV2) versus V_{13}

- **Window 5:** The refractive indices profiles (RIP) of the fibre are shown. The blue line shows the RIP of Core which varies from 1.4475 @ 1.3 µm to 1.444 @1.6 µm. The RIP of first cladding is the green line which varies from 1.445 @ 1.3 µm to 1.4425 @1.6µm. Finally the red line indicates the RI of outer cladding which varies from 1.4474 @1.3 µm to 1.4435 @ 1.6 µm.

- **Window 6:** shows the spot-size of the DFF. This varies with the wavelength and similar with case study 1 for its effective area.

- **Window 7:** shows the rise time budget of the fibre. The green line is the theoretical value, which is taken as **0.5/40 ns**. The reason being that we are taking NRZ format, which is taken theoretically as **0.75/40 ns**. But taking practical considerations the value is decreased to **0.5/40 ns**.

- **Window 8:** gives the KAPPA value which satisfies the criteria for a Kappa value approaching unity.

- **Window 9:** gives the DL product of the dispersion-managed link, which is very close to Null, hence error-free transmission is expected.

M. Design Summary

From the design case studies illustrated above it can be concluded that the fiber types J, B and E satisfy the specification of dispersion having less than 3 ps/(nm-km) in a wider spectral range (i.e. 1280 nm to 1620 nm) and the total dispersion in this region is almost uniform with very low dispersion ripple (2 ±0.01 ps/(nm-km)). Waveguide dispersion parameter $Vd^2(Vb)/dV^2$ curve can be modeled to obtain the total waveguide dispersion in triple-clad step-index optical fiber. The extreme sensitivity (88.88 unit dispersion per unit µm) of the fiber total dispersion to variation in core radius (a_0) is a unique property of all dispersion - flattened fibers and dispersion-compensated fibers. The changes in outer cladding refractive index are critical (i.e. 142,850 unit dispersion per unit refractive index). Doping concentration has a little effect on the total dispersion (i.e. 0.5 unit dispersion per unit concentration).

The changes in core radius, a_0 and outer cladding, n, are very sensitive to the total dispersion. Thus the contributions of these two parameters should be considered before varying other five parameters. By analyzing the effects of each of the seven geometrical and index profile parameters and the contribution of material dispersion due to different types of a set of materials as core or cladding to the waveguide dispersion factor, one could design the triple-clad profile to satisfy any dispersion flattening and compensating factors over an ultra-wide spectral range as illustrated in the two design cases.

CONCLUSIONS

The demands of optical fibres having non-zero flattened and corresponding compensating dispersion factors over the ultra-wide spectral band of 1300 nm to 1550 nm (and even wider), this paper has describes in details the strategy and design procedures for tailoring the dispersion properties of optical fibers having triple-clad index profiles. The design has been limited by several stringent conditions of the seven geometrical and index profile parameters. We have presented a number of efficient design algorithms based on the approximation and fitting the saddle points of the waveguide dispersion curves. Surprisingly these points follow a simple cubic function. A very accurate prediction of the waveguide dispersion is described allowing designing a best-fit curve to tailor the total dispersion factor over a ultra-wide spectrum. This has been demonstrated in the two case studies using different core materials.

Varying the seven degrees of freedom based on the geometrical and index parameters the effects of core and cladding radii, refractive indices and doping concentrations on the total dispersion are analyzed and the design sensitivities are drawn. Our design algorithms ensure a systematic sequence to satisfy stringent design specifications with ease. The developed method presented in this paper is valid and applicable to other geometrical and index profiles.

The sensitivity of these dispersion flattening and compensating fibers to the polarization dispersion is of much interest and will be reported in the near future.

The design guidelines presented herewith would be applicable to the design and manufacturing of broadband dispersion flattened and dispersion compensation fibers for ultra-long reach and ultra-wideband DWDM optical fiber communications transmission systems.

REFERENCES:

[1] L.N. Binh. and H.C. Chong, “Dense wavelength division multiplexing packet switching networks”, J. Elect. Electron. Eng. (Aust), pp. 178-195, Sept. 1994 - and references therein.

[2] see for example: M. Nakazawa et al., “Field demonstration of soliton transmission at 10 Gbits/sec. over 2,500 Km and 20 Gb/sec. over 1,000 km in the Tokyo metropolitan optical network”, Proc. 10th Int. Conf. Integrated Optics and Optical Com., Post Deadline paper PD 2-1, vol. 4, Hong Kong, June 1995; A. Wedding, “New method for optical transmission beyond dispersion limit”, Elect. Lett., vol. 28, pp. 402-404, 1993.

[3] N. Nakazawa, and H. Kubota, “Optical soliton communication in a positively dispersion-allocated optical fiber transmission line”, Elect. Lett., vol. 31, pp. 216-217, 1995.

[4] R. Ohhira, A. Hasegawa and Y. Kodama., “Methods of constructing a long haul soliton transmission system with fibers having a distribution in dispersion”, Opt. Lett., vol. 20, pp. 701-703, 1995.

[5] See for examples and references therein: L.N. Binh and S.V. Chung, “A generalized approach to single-mode dispersion-modified optical fiber design”, Opt. Eng., 1996.

[6] G.P. Agrawal, “Fiber-optic communications systems”, Wiley, 1992.

[7] A.W. Snyder, "Understanding Mono-mode Optical Fibers", Proc. IEEE, vol. 69, No. 1, Jan 1981, pp 6-13.

[8] D. Marcuse, "Loss-Analysis of Single-Mode Fiber Splices", Bell Syst. Tech. J., vol. 56, No. 5, 1977, pp 703-718.

[9] Y. Li, C.D.Hussey, and T.A. Birks, “Triple-clad single-mode fibers for dispersion shifting”, IEEE J. Lightwave Tech., LT-11, pp. 1812-1819, 1993.

[10] Y. Li and Hussey C. D., “Triple-clad single-mode fibers for dispersion flattening”, Opt. Eng., vol. 33, pp. 3999-4005, 1994.

[11] Liu, Y., V.L. Da Silva., A. A. J. Bhagavatula, D.Q. Chowdhury, and M.A. Newhouse., “ Single-mode dispersion shifted fibers with large effective area for amplified systems”, IOOC’95 Postdeadline paper PD-2-9, pp. 37-38, Hong Kong, June 1995.

[12] The MathWorks Inc., “MATLAB high performance numeric computation”, Aug. 1982.

[13] S.V Chung., “Simplified analysis and design of single mode optical fibers”, Ph. D. dissertation, Monash University, Australia, 1987.

[14] See for example and references therein C.D. Poole, J.M. Wiesenfeld, D.J. DiGiovanni and A.M. Vengsarkar, “Optical fiber-based dispersion compensation using higher order modes near cut-off”, IEEE J. Lightw. Tech., vol. 12, Oct. 1994, pp. 1746-1758.

[15] L. B .Jeunhomme, “Single Mode Fibre Optics, Principles and Applications”, DekkerPub 1983.

[16] M. Monroe , "Propagation in Doubly Clad Single Mode Optical Fibres", IEEE Journal of Quantum Electronics, vol QE-18, No 4, pp 535-542, April 1992.

[17] L.N. Binh "Design guidelines for ultra-broadband dispersion flatten optical fibres with segmented core index profile", Department of Electrical and Computer Systems Eng, Monash university, Technical report No. MECS14.003.http://www.ds.eng.monash.edu.au/techrep/reports/post2003index.html

[18] K. Thyagrajan, R.K.Varshney, P.Palai, A. K. Ghatak, and I.C. Goyal, "Novel design of a dispersion compensating fibre", IEEE Photonics Tech Lett, Vol 8, No 11, pp 1510-1512, Nov-1996.

[19] F. Forghieri, R. W.Tkach, A.R. Chraplyvy, A.M Vengsarkar, AT&T Bell Laboratories, "Dispersion Compensating Fibre: is there a figure of merit", OFC'96 Technical Digest, pp 255-256.

[20] G.E. Berkey, M.R. Sozanki, "Negative Slope Dispersion Compensating Fibres", Science and Technology Division, Corning, WM14-1-WM14-3.

[21] M. Hirano, A. Tada, T. Kato, M. Onishi, Y. Makio, M. Nishimura, "Dispersion Compensating Fibre over 140 nm-Bandwidth", Proc. 27th ECOC. Th.M.1.4, 494-495.

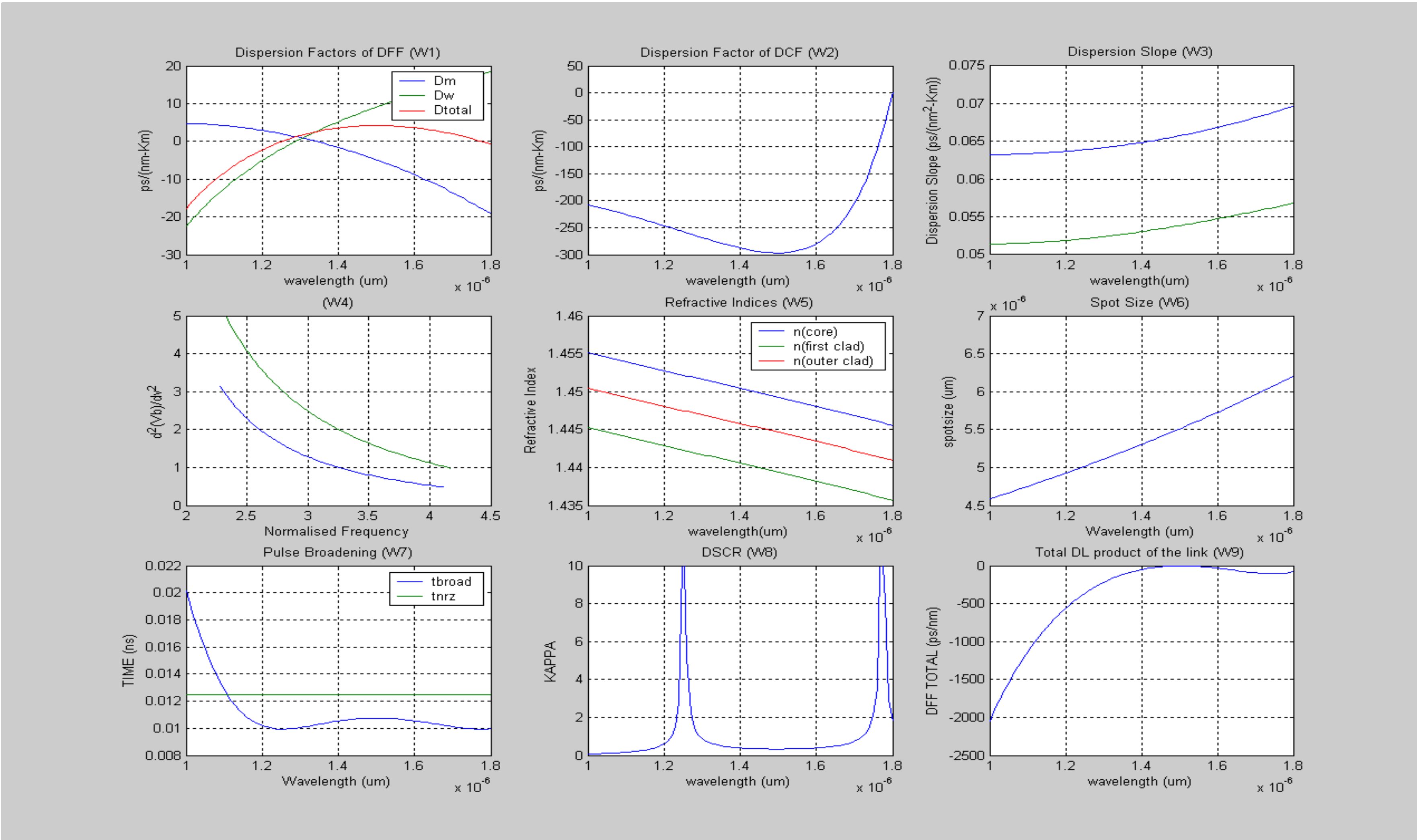

Dispersion Factors of DFF (W1)
ps/(nm-Km)
wavelength (um)
x 10^-6
Dm
Dw
Dtotal
Dispersion Factor of DCF (W2)
ps/(nm-Km)
wavelength (um)
x 10^-6
Dispersion Slope (W3)
Dispersion Slope (ps/(nm^2-Km))
wavelength(um)
x 10^-6
(W4)
d^2(Vb)/dv^2
Normalised Frequency
Refractive Indices (W5)
Refractive Index
wavelength(um)
n(core)
n(first clad)
n(outer clad)
x 10^-6
Spot Size (W6)
x 10^-6
spotsize (um)
Wavelength (um)
x 10^-6
Pulse Broadening (W7)
TIME (ns)
Wavelength (um)
tbroad
tnrz
x 10^-6
DSCR (W8)
KAPPA
wavelength (um)
x 10^-6
Total DL product of the link (W9)
DFF TOTAL (ps/nm)
wavelength (um)
x 10^-6

FIGURE 19

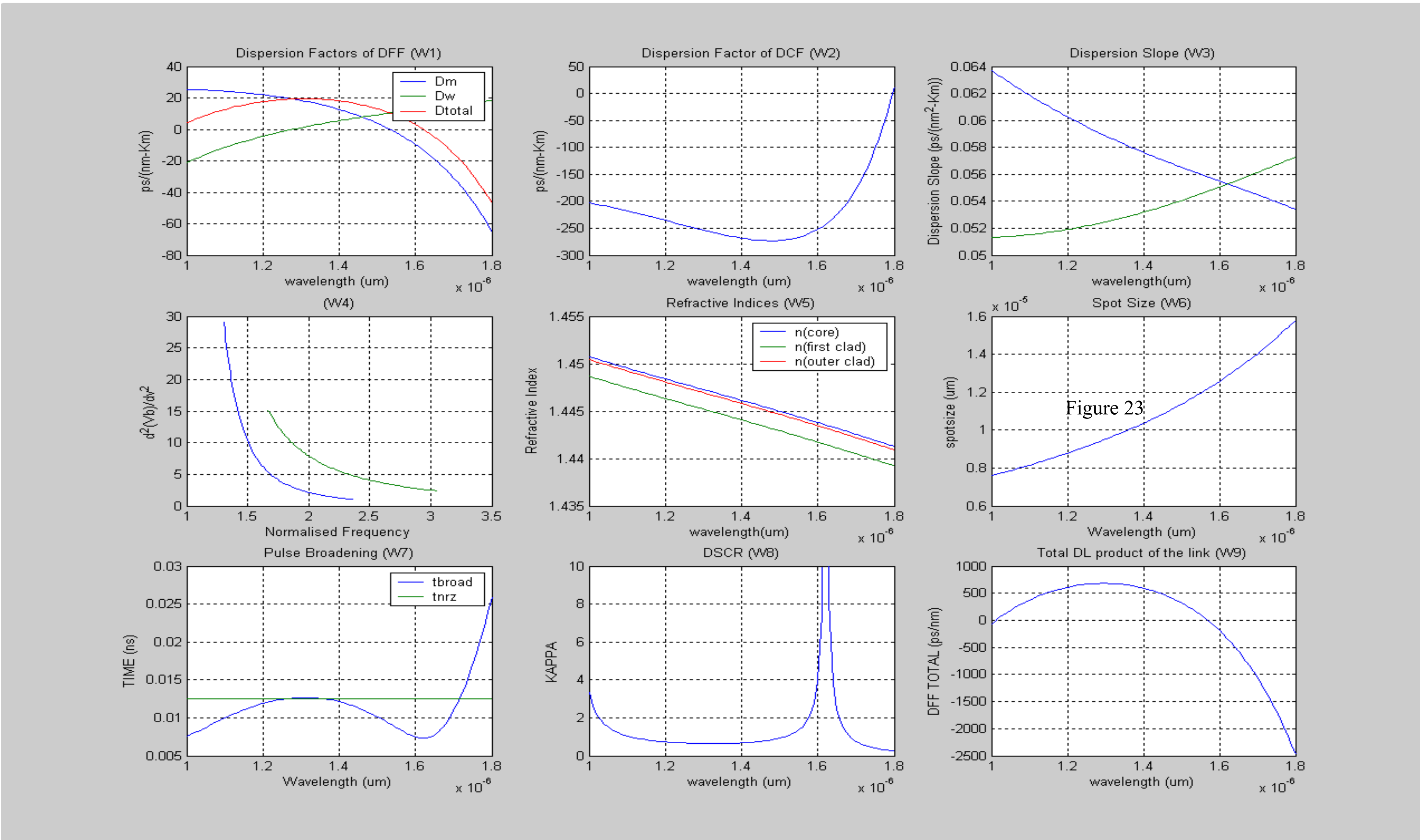

Dispersion Factors of DFF (W1)
Dm
Dw
Dtotal
ps/(nm-Km)
wavelength (um)
x 10^-6
Dispersion Factor of DCF (W2)
ps/(nm-Km)
wavelength (um)
x 10^-6
Dispersion Slope (W3)
Dispersion Slope (ps/(nm^2-Km))
wavelength(um)
x 10^-6
(W4)
d^2(Vb)/dv^2
Normalised Frequency
Refractive Indices (W5)
n(core)
n(first clad)
n(outer clad)
Refractive Index
wavelength(um)
x 10^-6
x 10^-5
Spot Size (W6)
spotsize (um)
Figure 23
Wavelength (um)
x 10^-6
Pulse Broadening (W7)
tbroad
tnrz
TIME (ns)
Wavelength (um)
x 10^-6
DSCR (W8)
KAPPA
wavelength (um)
x 10^-6
Total DL product of the link (W9)
DFF TOTAL (ps/nm)
wavelength (um)
x 10^-6

FIGURE 22