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DESIGN GUIDELINES FOR ULTRA-BROADBAND DISPERSIO
OPTICAL FIBRES WITH SEGMENTED-CORE INDEX PROFILE

Le Nguyen Binh

MONASH UNIVERSITY

DESIGN GUIDELINES FOR ULTRA-BROADBAND DISPERSION-FLATTENED OPTICAL FIBRES WITH SEGMENTED-CORE INDEX PROFILE

Le Nguyen Binh

Department of Electrical and Computer Systems Engineering, Monash University, P.O Box 35, Clayton Victoria 3800, Australia . E-mail le.binh@eng.monash.edu.au

Abstract

Single optical fibres exhibiting minimum dispersion over the two optical wavelength windows of 1300 and 1550 nm region are essential for the multi-channel operation of dense wavelength multiplexed systems and networks. Design guidelines of dispersion-flattened optical fibres, over a wide band of optical spectrum, which have a triple-clad or segmented-core distribution of step-index regions are developed in order to predict the dispersion curves representing the waveguide dispersion parameter and to adjust the dispersion flattening effect of triple-cladded index profile fibres. The flattening covers a wavelength range of more than 350 nm is achievable. The effects of the geometrical and index distribution parameters of the triple-clad to the characteristic of the total dispersion of the fibre are analysed. The guidelines are simple and logical for determining the main parameters and their sequence for tailoring the fibre dispersion characteristics and would be useful for systems engineers in understanding the fibre design process in the ultra-boradband optical networks.

Key words: optical fibres; optical fibre dispersion; wavelength division multiplexed optical fibre systems.

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1. INTRODUCTION

Single mode optical fibre 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 communcations system transmission employing wavelength multiplexing optical carriers. The demand to expand the transmission capacity requires investigation of wavelength division multiplexed telecommunications and the ulse broadening effects of optical fibres over the optical spectrum. The availability of single mode optical fibres with a minimum and flattened characteristics in dispersion and insensitive to microbending loss and other additional losses will enhance the system engineering of these fibres. In addition the commercial availability of Er:doped fibre amplifiers together with the new fabrication techniques of suppressed OH-peak loss fibres have allowed system designers to investigate the use of near-zero dispersion optical fibres to extend the repeaterless distance. Optical amplifiers using Pr:doped glass for the 1310 nm have also been developed and would be potentially used for optical fibre systems and networks. 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 desired for maximising the capacity of the optical transmission medium. It is thus required to design and develop optical fibres that would exhibit minimum and flattened dispersion characteristics over this ultra-broadband spectral range. A total transmission capacity reaching 10 tera-bps would thus be foreseeable in the near future. Furthermore practical demonstrations of optical soliton fibre systems[2] have attracted interests to design of optical fibres which exhibit appropriate dispersion property to design dispersion-allocated[3] or dispersion-managed[4] optical fibre systems. Future optical soliton transmission systems require accurate prediction of the dispersion factor of fibres in each section of transmission distance.

Advanced design of single mode fibres with multiple core index profile have been reviewed in numerous papers[17,18] and was the subject of intensive research and development in the mid-1980s[15]. Recently we have introduced key strategies for the design of optical fibres with modified dispersion characteristics[5] in which a new algorithm has been described for finding the saddle point of the waveguide dependent parameter which strongly influences the waveguide dispersion factor for simplifying further the design of the dispersion profile of single mode fibres to ensure minimum dispersion. The segmented core structure, a W-profile, has also been designed and fabricated recently for demonstration of a very high negative dispersion compensating fibre[16].

In this paper we present the following aspects of dispersion flattening in a non-uniform core optical fibre as follows. In the next section the background for modelling of dispersion flattened triple-clad fibre 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 fibres. Section 3 then gives the design guidelines for design of non-uniform core index profile to achieve significantly large waveguide dispersion to equalise that of the material dispersion. In particular the operating regions of the waveguide parameters to obatin such equalisation. Simulated results and discussions will be given in Sections 4 with concluding remarks given in Section 5.

2. IMPORTANT DESIGN PARAMETERS

2.1 The Group Velocity Dispersion (GVD)

The total dispersion parameter, *D* in the unit of ps/(km-nm) of a single optical fibre 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 fibres with dispersion flattened characteristics.

In case that the higher order dispersion is necessary the third order effect, dispersion slope, 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 a optical fibre is due to the refractive index of silica, the material used for fibre fabrication, changes with the optical frequency. The refractive index $n(\lambda)$ 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 fibres in Table 1. The first three Sellmeier terms, ie. M = 3, are used.

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

$$\frac{dn(l)}{dl} = \frac{\sum_{j=1}^{3} \left\{ \frac{2\,lB_j}{l^2 - l_j^2} \left(1 - \frac{l^2 B_j}{\left(l^2 - l_j^2\right)} \right) \right\}}{2\sqrt{1 + \sum_{j=1}^{3} \frac{l^2 B_j}{\left(l^2 - l_j^2\right)}}} \tag{5}$$

the second derivative given by

$$\frac{d^2 n(l)}{dl^2} = \frac{\sum_{j=1}^{3} \frac{2B_j}{l^2 - l_j^2} \left(1 - \frac{5\,l^2}{\left(l^2 - l_j^2\right)} + \frac{4\,l^4}{\left(l^2 - l_j^2\right)^2} \right)}{2\sqrt{1 + \sum_{j=1}^{3} \frac{l^2 B_j}{\left(l^2 - l_j^2\right)}}} - \frac{\sum_{j=1}^{3} \frac{2\,lB_j}{l^2 - l_j^2} \left(1 - \frac{l^2}{\left(l^2 - l_j^2\right)} \right)}{4\left(1 + \sum_{j=1}^{3} \frac{l^2 B_j}{\left(l^2 - l_j^2\right)}\right)^{\frac{3}{2}}} \tag{6}$$

and third derivative given by

$$\begin{aligned} \frac{d^3 n(l)}{dl^3} = {} & \frac{3\sum_{j=1}^{3} \frac{2\,lB_j}{l^2 - l_j^2} \left(1 - \frac{l^2}{\left(l^2 - l_j^2\right)} \right)}{8\left(1 + \sum_{j=1}^{3} \frac{l^2 B_j}{\left(l^2 - l_j^2\right)}\right)^{\frac{5}{2}}} + \frac{\sum_{j=1}^{3} \frac{24\,lB_j}{l^2 - l_j^2} \left(-1 + \frac{3\,l^2}{\left(l^2 - l_j^2\right)} - \frac{2\,l^4}{\left(l^2 - l_j^2\right)^2} \right)}{2\sqrt{1 + \sum_{j=1}^{3} \frac{l^2 B_j}{\left(l^2 - l_j^2\right)}}} \\ & - \frac{3\left\{ \sum_{j=1}^{3} \frac{2B_j}{l^2 - l_j^2} \left(1 - \frac{5\,l^2}{\left(l^2 - l_j^2\right)} + \frac{4\,l^4}{\left(l^2 - l_j^2\right)^2} \right) \right\} \left\{ \sum_{j=1}^{3} \frac{2\,lB_j}{l^2 - l_j^2} \left(1 - \frac{l^2}{\left(l^2 - l_j^2\right)} \right) \right\}}{4\left(1 + \sum_{j=1}^{3} \frac{l^2 B_j}{\left(l^2 - l_j^2\right)}\right)^{\frac{3}{2}}} \end{aligned} \tag{7}$$

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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 wavelength range of 1.25 µm - 1.66 µm, it can be approximated by an empirical relation [6] given by :

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

where λ_{ZD} is 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 fibres 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 eqn. (1) depends on the *V* parameter of the fibre and is given by [6] :

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

where *V* is the normalised frequency of the fibre and b is the normalised propagation constant. It can be seen later that this parameter is defined for different regions in the core and cladding. The normalised propagation constant *b* for a specific fibre is only dependent on *V*, then the normalised waveguide dispersion parameter $Vd^2(Vb)/dV^2$ also depends on *V*. This latter function is another well-known universal parameter which plays a central role in the effects of pulse spreading in single mode step-index fibres.

For doped silica fibres, the attenuation minima are in the 1300 nm and 1550 nm wavelength windows. A multiple-index-layer fibres (eg. dispersion-flattened fibres) 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 (ie. depressed cladding) [5].

The relationship between the structural geometry and index profile of the triple-clad fibre and their total dispersion and the fundamental mode spot sizes are examined. The sensitivity of the total dispersion of fibres due to changes in the structural parameters (a_0, a_1 a_2, n_0, n_1, n_2, n_3, n) is alo investigated. These structural parameters which describes the fibres geometry and index profile are used to design optical fibres having ten different fibre material type as core materials in order to meet the requirement of maximum dispersion not higher than 3 ps/(nm.km), as an example, in the wavelength range of 1300 to 1580nm.

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, it is important to understand the effect of each structural parameters before designing the fibre. Eqn.(10) clearly shows that the waveguide dispersion depends on the waveguide dispersion parameter, $Vd^2(Vb)/dV^2$. Numerous attempt to approximate this equation to represent this curve. Thus, the modelling of this curve is to be determined prior to designing the fibre.

2.2. Profile Construction

The refractive index profile of the triple-clad step-index fibre is shown schematically in Figure 1(a). Figure 1(b) shows the unnormalised profile and Figure 1(c) shows the normalised 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]

$$\Delta_i = \frac{n_i - n}{n} \tag{11}$$

The normalised outer radius is defined as

$$S_i = \frac{a_i}{a_0} \tag{12}$$

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

$$D_i = \frac{\Delta_i}{\Delta_0} \tag{13}$$

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 (Fibre 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 fibres. Considerations are made for these laterials for 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. For minimising the difficulty of manufacturing the fibre the limit of 3 ps/(nm.Km) is sufficient for large bandwidth-length product.

A simulation program using **MATLAB â** for triple-clad dispersion-flattened single mode fibres is developed in which ten different material types (type A to type J) of single-mode triple-clad optical fibres 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 waveguide dispersion parameters D_W can be determined as there is no exact expression to represent the curve. Seven fibre parameters used are 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). They constitute seven degrees of freedom in designing these fibres. The effects of these parameters on total dispersion has been studied and analysed. Futher the effects of the doping concentration on total dispersion are discussed. All the case studies of the effect of changing structural parameters on total dispersion are conducted using fibre *type A*, ie. pure silica.

2.3 Waveguide Property of The Triple-Clad Optical Fibre

The transverse propagation constant ***u/a*** and transverse decay constant ***v/a*** are well known and given for the core and the fist and second ladding layers respectively of the segmented core index profile fibres as

$$u_0 = a_0\sqrt{k^2 n_0^{\ 2} - \boldsymbol{b}_0^{\ 2}} \tag{14a}$$

$$u_1 = a_1\sqrt{k^2 n_1^{\ 2} - \boldsymbol{b}_1^{\ 2}} \tag{14b}$$

$$u_2 = a_2\sqrt{k^2 n_2^{\ 2} - \boldsymbol{b}_2^{\ 2}} \tag{14c}$$

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

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

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

where β_0, β_1 and β_3 are the propagation constants of the guided waves in the core and first and second cladding layers of the segmented core fibre 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 normalised frequencies for all layers can be expressed as

$$V_0 = a_0k\sqrt{n_0{}^2 - n^2} \tag{18a}$$

$$V_1 = a_1k\sqrt{\left|n_1{}^2 - n^2\right|} \tag{19b}$$

$$V_2 = a_2k\sqrt{n_2{}^2 - n^2} \tag{19c}$$

Furthermore an effective normalised frequency can be defined as

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

The spot size r_0 can be found by an empirical approximation [6] or analytical method[7]:

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

the spot size is chosen appropriately so that there is a minimum dispersion and satisfy the requirement for maximum power coupling. Further the normalised intensity *I(r)* 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 the segmented core are the extension of (10) are defined as:

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

$$D_{w1} = -\left(\frac{n_1 - n_2}{lc}\right)V_1 \frac{d^2(V_1 b)}{dV_1^{\,2}} \tag{23b}$$

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

where the normalised waveguide dispersion coefficient is $Vd^2(Vb)/dV^2$. For triple-clad fibre we have the following three normalised 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 modified Bessel functions with order *i-th*. Finally, it is straightforward to find the triple-clad (or segmented core) tal dispersion given by

$$D_{TOT} = D_M + D_{W0} + D_{W1} + D_{W2} \tag{26}$$

3. 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, neither simple approximation nor exact representation of $Vd^2(Vb)/dV^2$ curve is found in any papers. Most published works[9,10] and the algorithm developed in Ref.[13] are far too complicated to analyse, particularly at the design inception stage. Therefore, this section outlines an *algorithm* to predict the behaviour of the $Vd^2(Vb)/dV^2$ curve in the following steps.

<u>STEP 1</u>

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

$$\left(V\frac{d^2(Vb)}{dV^2}\right) = V^3 \tag{27}$$

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 eqn. (27) if required, mainly the constant of the cubic equation. Higher order polynomial is found to be unnecessary in this case.

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 eqn. (27) :

$$Cx = Dx - \frac{Dy}{\left(\frac{d}{dV}\left(\frac{Vd^2(Vb)}{dV^2}\right)_{at(Dx,Dy)}\right)} \tag{28}$$

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 eqn. (28).

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

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 that are shown in Figure 5 have to be represented by a general mathematical expression as a function of wavelength. Thus, a polynomial of *9-th* order given by eqn. (29) has been chosen for this purpose. For single-mode, the normalised frequency is given by,

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

where l_{ci} is the cutoff wavelength for single-mode. Hence, the *9-th* order of $Vd^2(Vb)/dV^2$ polynomial can be approximated by,

$$V\frac{d^2(Vb)}{dV^2} = P_0 + P_1\left(\frac{2.405\,l_c}{l}\right) + P_2\left(\frac{2.405\,l_c}{l}\right)^2 + P_3\left(\frac{2.405\,l_c}{l}\right)^3 + \ldots + P_9\left(\frac{2.405\,l_c}{l}\right)^9 \tag{31}$$

or

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

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

4. EFFECTS OF WAVEGUIDE PARAMETERS ON DISPERSION FLATTENING

The design presented in this paper involves seven degrees of freedom. By analysing the effects due to each individual parameter we are able to predict the changes of the dispersion factor and identify the main factors that would play major role in the tailoring of this factor. Ten different types of fibre materials listed in Table 1 have been used in the core/cladding regions to design dispersion flattened fibres in order to meet the requirement.

In searching for an appropriate materials for flattening of the total dispersion curves, material types A, B, C, D, E, F, G, I and J are used as core and cladding materials for the design testing of optical fibres satisfying the upper limit of the dispersion-flattening. Material type H has the total dispersion of about 9 ps/(nm-km) in the range 1300-1580 nm which is slightly above the design specification. Fibres employing material type J give the best flattening of the dispersion, less than 3 ps/(nm-km) from 1280 nm to 1620 nm can be achieved. There is also a maximum of three zero dispersion points. As an example the dispersion curves for material type B are illustrated in Figure 7. They indicate the flatness of the dispersion curves but well above the zero line of the dispersion. The first and second zero dispersion points are approximately located in the two fibre 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. We believe that this type J can be used to flatten the dispersion below 1.0 ps/nm-km. However the demands on the fabrication would be high. Rather we would recommend that a dispersion compensation fibres whose overall dispersion slope would also match with those of the dispersion flattening fibres.

4.1 Effect of core and cladding radii on total dispersion

Referring to Figures 8, 9 and 10, various curves of core/cladding radius against total dispersion are plotted. We observe the following effects of each core/cladding radius on the dispersion characteristics as follows:

(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 analysing the behaviour of the dispersion curves, we obtain the maximum sensitivity of changes in a_0 to total dispersion in the fibre windows region is about 88.88 ps/(nm-km-μm).

(ii) As the first cladding radius, a_1, is reduced the total dispersion curve is shifted upwards. By analysing the results the maximum sensitivity of changes in a_1 to total dispersion in the fibre windows region of 64.68 ps/(nm-km-μm) 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 fibre windows region of 0.99 ps/(nm-km-μm) is obtained.

From the above results, it is concluded that the change in core radius, a_0 is very sensitive to the total dispersion (ie. 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 fibre. The sensitivity of each core radius is compared with respect to that of the second cladding layer as shown in Table 2. It confirms the most sensitivity factor is the core radius. Thus the manufacturing tolerance of the fibre core radius must be controlled accurately as compared to those of the cladding layers.

4.2 Effect of Refractive Indices of the cladding layers on Total Dispersion

In Figures 11, 12, 13 and 14, the fibre total dispersion are plotted for various values of the core and cladding refractive indices. These curves show the following effects due to cladding and core regions:

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

(ii) When the first cladding refractive index, n_1, is increased the total dispersion curve is shifted upwards but the first zero dispersion point are shifted to the higher wavelength. By analysing the results, we have obtained the maximum sensitivity of changes in n_1 to total dispersion in the fibre 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 indicate that the maximum sensitivity of changes in n_1 to total dispersion in the fibre windows region is 6666 ps/(nm-km) per unit refractive index.

(iv) As the outer cladding refractive index, n, is decreased the total dispersion curve is shifted upwards and the first and second zero dispersion points are shifted to the higher wavelength leading to a maximum sensitivity of changes in n_1 to total dispersion in the fibre windows region of 142,850 ps/(nm-km) per unit refractive index.

Therefore it can be concluded 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 dispersion behaviour of the segmented core index optical fibre. The normalised 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 normalisation 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 fibre.

4.3 Effect of Doping Concentration on the Total Dispersion

Referring to Figure 14, 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 significant role in the flattening of the total dispersion curve. The doping concentration should be the last factor to alter in the design of the triple-clad step-index fibres. This factor, however should be considered for its contribution to the attenuation of optical signals.

4.4 Remarks on design guidelines

Detailed investigations of the behaviour of fibres of ten different materials indicates that fibre type J meets the specification of having less than 3 ps/(nm-km) in a wider range (ie. 1280 nm to 1620 nm) and its total dispersion in this region is almost constant (2 ps/nm-km). The waveguide dispersion parameter $Vd^2(Vb)/dV^2$ is modelled by using the *algorithm* in the previous section to obtain the total waveguide dispersion in triple-clad step-index optical fibre. The extreme sensitivity (88.88 unit dispersion per unit) of the fibre total dispersion to variation in core radius (a_0) is a unique property of all dispersion-flattened fibres. Changes in outer cladding refractive index is critical as well (ie. 142,850 unit dispersion per unit refractive index). Doping concentration has a little effect on the total dispersion (ie. 0.5 unit dispersion per unit concentration).

A general design procedure for segmented core fibres can now be outlined in Figure 15. We again note that changes in core radius, a_0 and outer cladding, n, are very sensitive to the total dispersion. Therefore these two parameters are considered to be the principal degrees of freedom in the design. By analysing the effect of each of the seven geometrical and index profile parameters , one could design triple-clad or segmented core fibres to any specification including those require high negative dispersion factors for disperson compensation.

5. CONCLUDING REMARKS

The requirement of low dispersion of less than 3 or 1 ps/(nm-km) over the wide band of operational wavelength 1300 nm to 1550 nm (and higher) in the design of optical fibres with triple-clad index profiles places several stringent conditions of the seven geometrical and index profile parameters. This requires a simplified approach that would give a logical sequence of design considerations. We have presented an efficient algorithm based on the investigation and fitting the saddle points of the curves that represent the waveguide dispersion factor. Surprisingly these points follow a simple cubic curve. A very accurate prediction of the waveguide dispersion is described allowing us to design a best fit curve to tailor the total dispersion factor over the wide range of wavelength.

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 analysed and the design sensitivities are drawn. Our design algorithm ensures a systematic and logical sequence for reaching the design specifications with ease. The developed method presented in this paper is valid and applicable to other geometrical and index profiles. These are the topics that would be reported in future works.

The design guidelines presented herewith would be applicable to the design of broadband two-mode dispersion compensation fibres, that is when the fibre is operating near the cut-off region and at the onset of the appearance of the higher order linearly polarised mode (LP_{11}). Such two-mode dispersion compensating fibres have been investigated and attracted attention in recent search for a universal broadband dispersion compensator.

REFERENCES:

1. Binh, L. N. 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: Nakazawa, M. et al., "Field demonstration of soliton transmission at 10 Gbits/sec. over 2,500 Km and 20 Gbits/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. Nakazawa N. and Kubota H., "Optically soliton communication in a positively dispersion-allocated optical fibre transmission line", Elect. Lett., vol. 31, pp. 216-217, 1995.

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

5. See for examples and references therein: Binh, L.N and Chung S. V., "A generalised approach to single-mode dispersion-modified optical fibre design", Opt. Eng., 1996.

6. G.P. Agrawal, "Fiber-optic communications systems", Wiley, 1992.

7. A.W. Snyder, "Understanding Monomode Optical Fibres", Proc. IEEE, vol. 69, No. 1, Jan 1981, pp 6-13.

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

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

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

11. Liu, Y., Da Silva V. L., Antos A. J. Bhagavatula, Chowdhury, D. Q., and Newhouse, M. A., “ Single-mode dispersion shifted fibres 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. see for example

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

Le N. Binh and S.V. Chung, “L.N. Binh and S.V. Chung, “Generalised approach to single-mode dispersion modified optical fibre design”, Optical Engineering, vol. 35, Aug. 1996, pp.2250-2261.

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

15. V. A. Bhagavatula et al., “segmented coresingle mode fibres with low loss and low dispersion”, Elect. Lett., vol. 19, pp.317-318, 1983.

16. J.L. Auguste, R. Jindal, J.-M Blondy, M. Clapeau, J. Marcou, B. Dussardier, G. Monnom, D.B. Ostrowsky, B.P. Pal and K. Thyagarajan, “-1800 ps/nm-km chromatic dispersion at 1.55 μm in dual concentric core fibre”, Elect. Lett., vol. 36, No. 20, Sep. 2000.

17. G.D. Khoe and H. Lydtin, “European optical fibres and paasive components: status and trends”, IEEE Trans. Select. Areas. Comms., vol. SAC-4, pp. 457-471, 1986.

18. D.M. Cooper et al., Dispersion shifted single mode fibers using multiple index structures”, Brit. Telecom. Tech. J., vol.3, pp. 52-85, 1985.

FIGURE CAPTIONS

Table 1 Sellmeier's coefficients for several optical fibre silica based material and doping concentration

Table 2 Normalised sensitivity comparison of core of the first and second cladding radii.

Table 3 Normalised sensitivity comparison of the refractive indices of the core, first, second and outer layers.

Figure 1 Refractive index profile of a triple-clad step-index-fibre indicating: (a) the label of each layer, (b) the unnormalised profile and (c) the normalised profile.

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

Figure 3 The $Vd^2(Vb)/dV^2$ family curve and eqn. (27).

Figure 4 Plot of the $Vd^2(Vb)/dV^2$ complete curve with respect to the V-parameter with a few predicted points.

Figure 5 Curves representing the optical waveguide dispersion parameter for the three cladding regions of the triple-clad step-index optical fibres.

Figure 6 Material, waveguide and total dispersion of the 'type A' triple clad step-index fibres.

Figure 7 The dispersion curves for fibres with material type B as the cladding materials.

Figure 8 Total dispersion factor versus wavelength with the core radius as a parameter for triple-clad step-index optical fibres.

Figure 9 Total dispersion factor as a function of wavelength with the first cladding radius as a parameter for triple-clad step-index optical fibres.

Figure 10 Total dispersion factor as a function of wavelength with the second cladding radius as a parameter for triple-clad step-index optical fibres.

Figure 11 Total dispersion factor versus wavelength with the core refractive index for triple-clad step-index optical fibres as a parameter.

Figure 12 Effects of the first cladding refractive index for triple-clad step-index optical fibres on the total dispersion factor.

Figure 13 The second cladding refractive index as a parameter in plots of total dispersion as a function of wavelength for triple-clad step-index optical fibres.

Figure 14 Total dispersion of the triple-clad step-index optical fibres with the most outer cladding refractive index as a parameter.

Figure 15 Total dispersion factor with respect to wavelength with the core doping concentration as a parameter.

Figure 16 Design algorithm flow chart for triple-clad optical fibre presented.

Fibre Type :	**Doping Conc:**	**$Si0_2$:**	**B1**	**B2**	**B3**	**l 1**	**l 2**	**l 3**
A	0%	100%	0.6961663	0.4079426	0.8974794	0.0684043	0.1162414	9.896161
B	3.1%	96.9%	0.7028554	0.4146307	0.8974540	0.0727723	0.1143085	9.896161
C	5.8%	94.2%	0.7088876	0.4206803	0.8956551	0.0609053	0.1254514	9.896162
D	7.9%	92.1%	0.7136824	0.4254807	0.8964226	0.0617167	0.1270814	9.896161
E	0%	Quenched	0.696750	0.408218	0.890815	0.069066	0.115662	9.900559
F	13.5%	86.5%	0.711040	0.408218	0.704048	0.064270	0.129408	9.425478
G	9.1%	90.9%	0.695790	0.452497	0.712513	0.061568	0.119921	8.656641
H	13.3%	86.7%	0.690618	0.401996	0.898817	0.061900	0.123662	9.098960
I	1%	99%	0.691116	0.399166	0.890423	0.068227	0.116460	9.993707
J	48.7%	51.3%	0.796468	0.497614	0.358924	0.094359	0.093386	5.999652

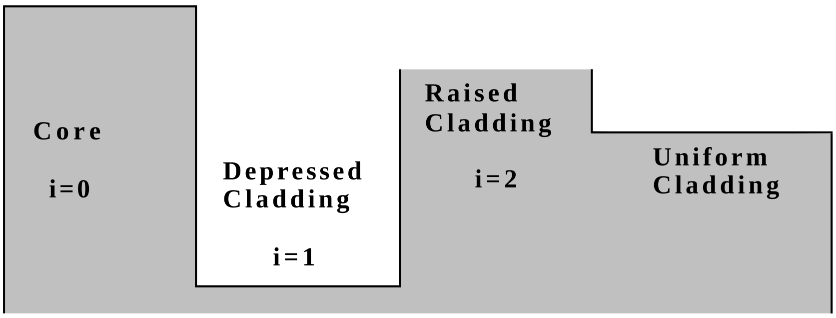
Table 1 : Sellmeier's coefficients for several optical fibre silica based material and doping concentration

	a_0	a_1	a_2
Normalised Sensitivity	89.7	65.3	1

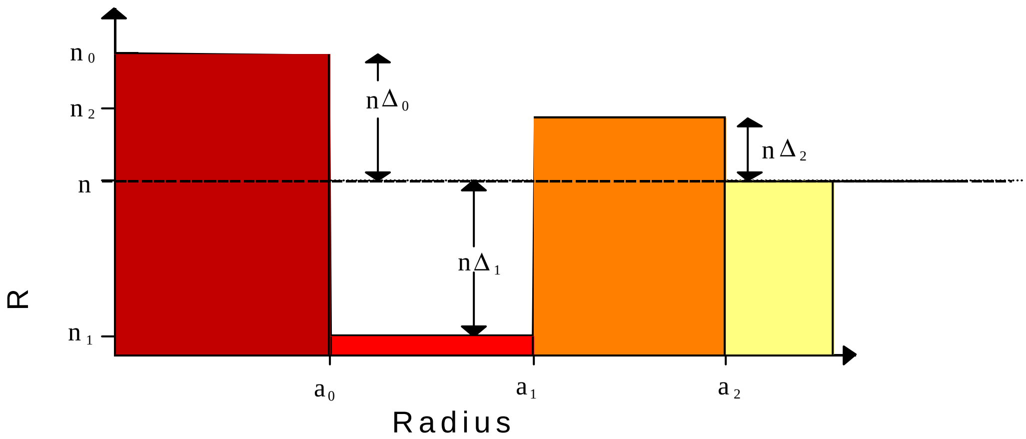
Table 2 Normalised sensitivity comparison of core, first and second cladding radius

	n_0	n_1	n_2	n
Normalised Sensitivity	7.50	8.88	1.00	21.43

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



(a)



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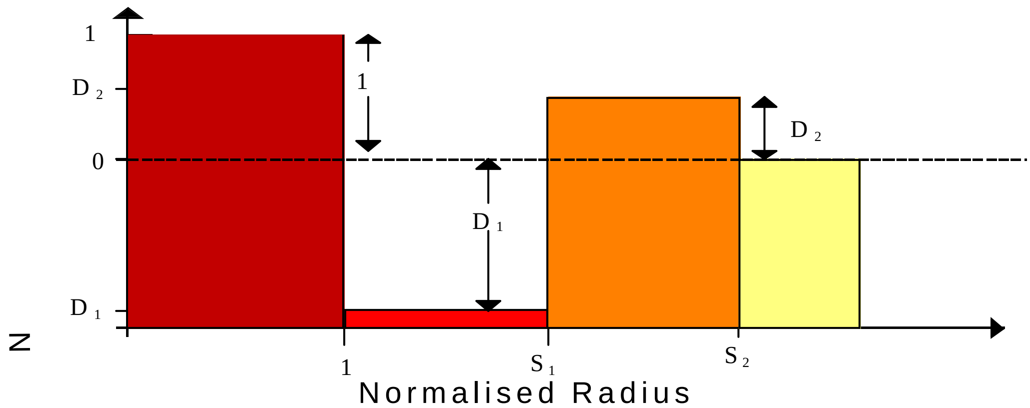

(c)

Figure 1 Refractive index profile of a triple-clad fibre indicating :

(a) the name of each layer, (b) the unnormalised profile, and (c) the normalised profile

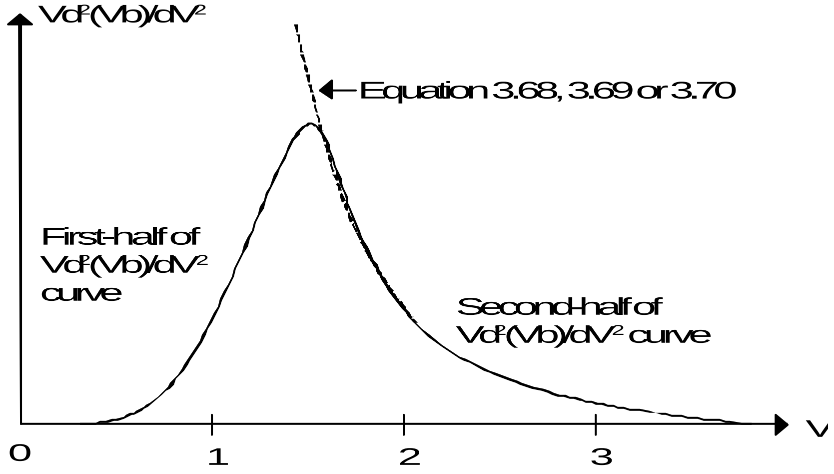

Figure 2 *Vd²(Vb)/dV²* complete curve, dotted line is obtained from (24a), (24b) and (24c).

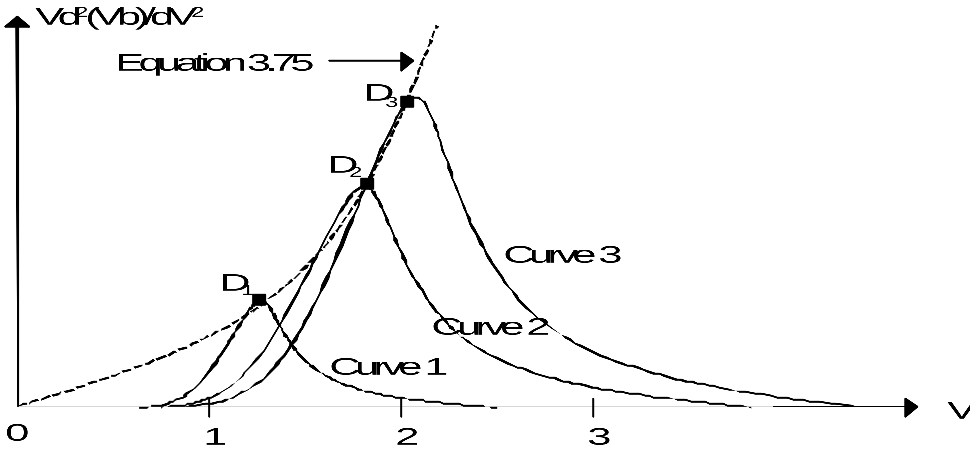

Figure 3 **Vd²(Vb)/dV²** family curves and (3.75)

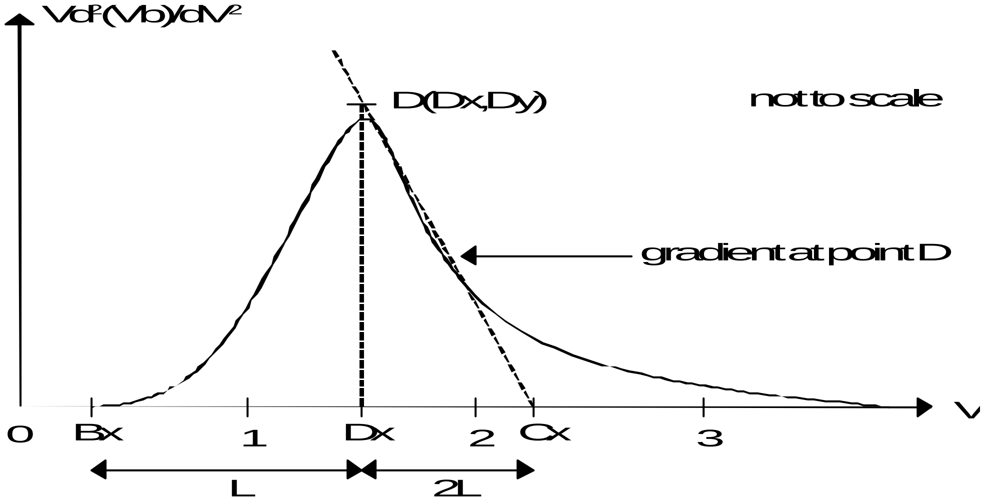

Figure 4 The variation of the waveguide parameter **Vd^2(Vb)/dV^2** complete curve with a few predicted points.

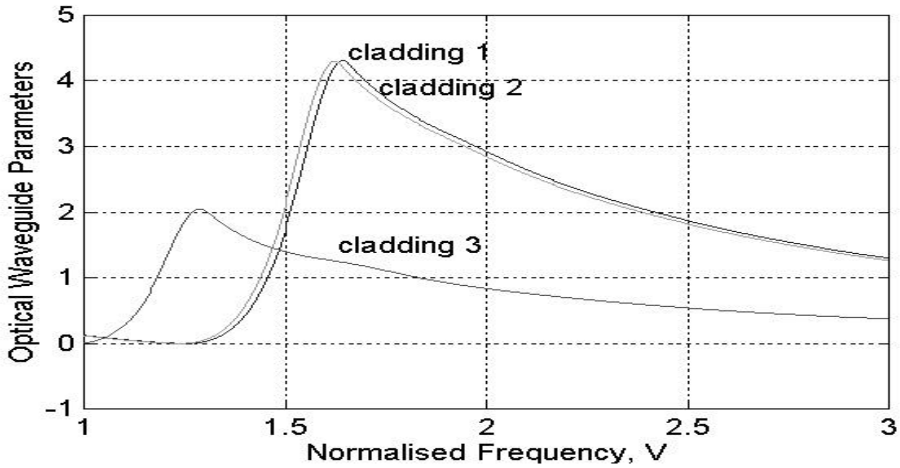

Figure 5 The optical waveguide parameter curves for optical fibres with three cladding types.

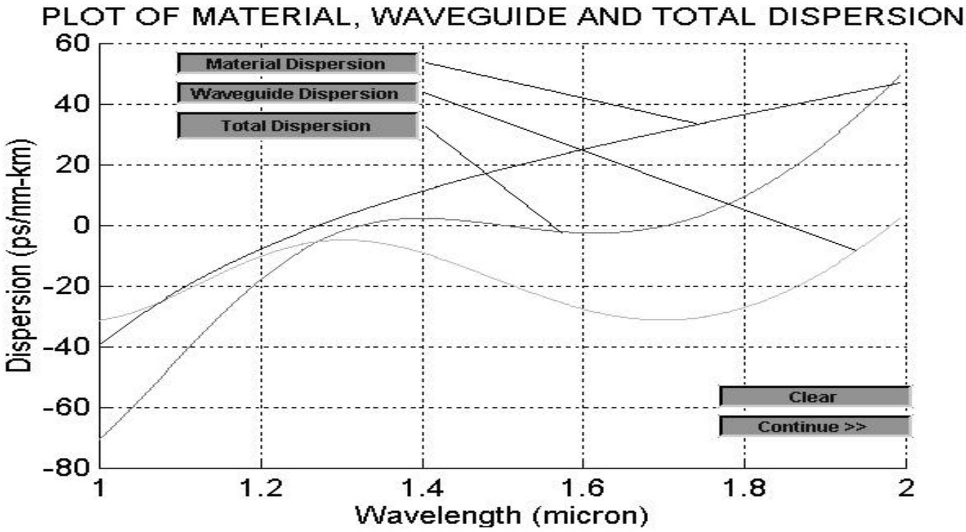

Figure 6 Material, waveguide and total dispersion of 'type A' triple clad optical fibre

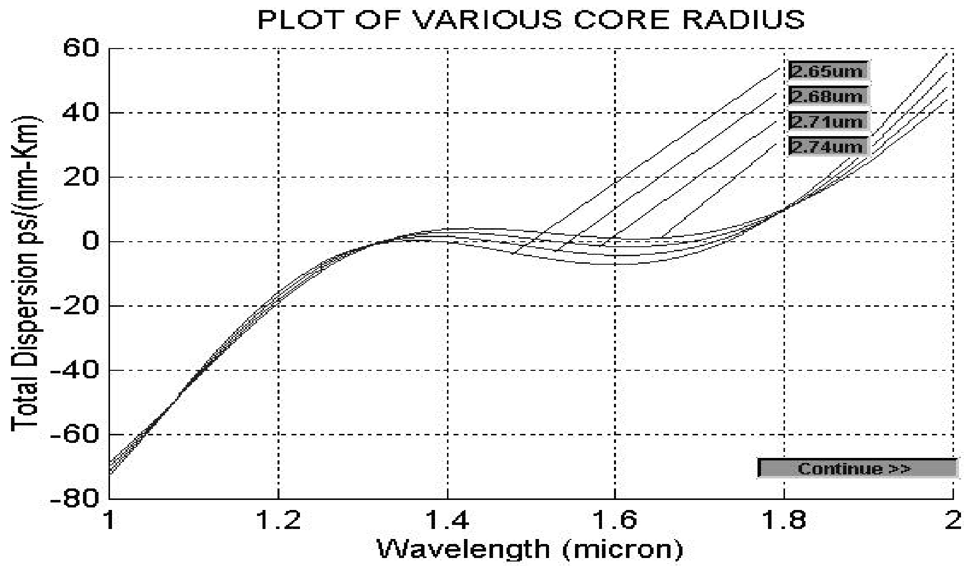

Figure 8 Total dispersion factor versus wavelength with the core radius of the triple-clad optical fibre as a parameter.

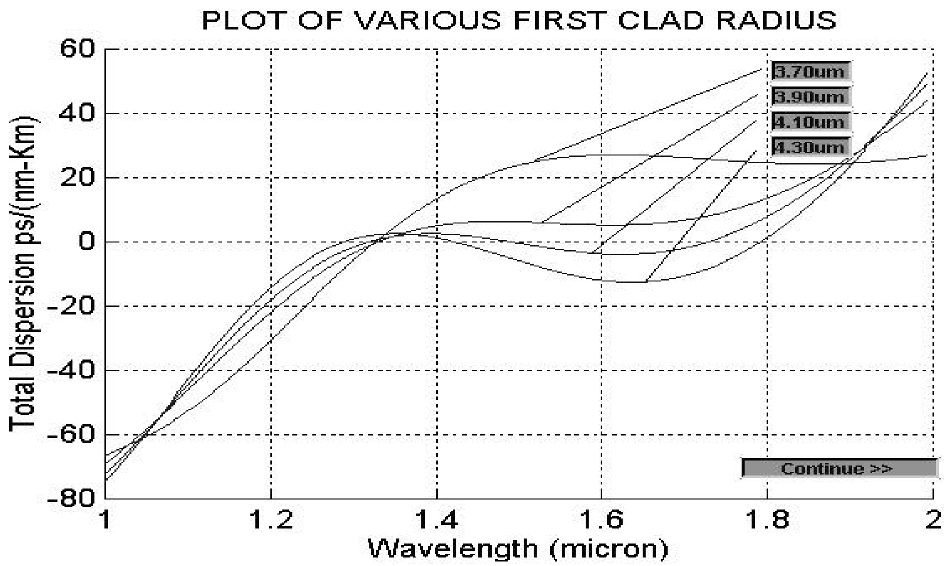

Figure 9 Total dispersion factor versus wavelength with the first-clad radius of the triple clad optical fibre as a parameter.

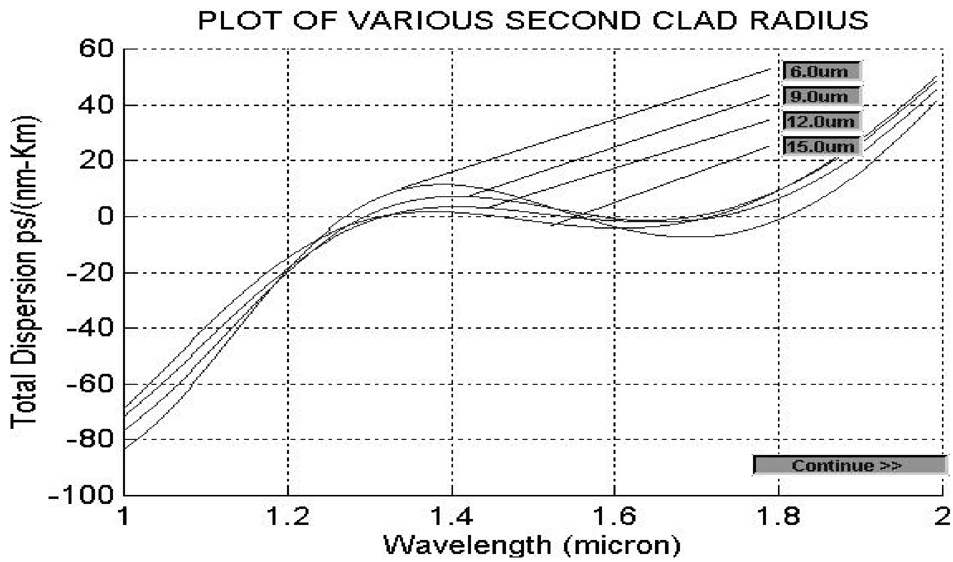

Figure 10 Total dispersion factor versus wavelength wth the second-clad radius of the triple clad optical fibre as a parameter.

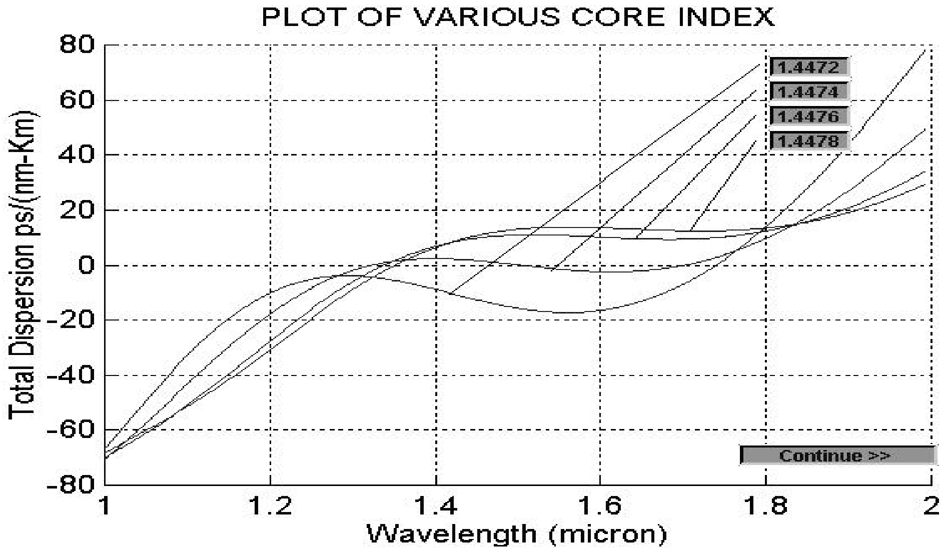

Figure 11 Total dispersion factor versus wavelength with the core refractive index of the triple-clad optical fibre as a parameter.

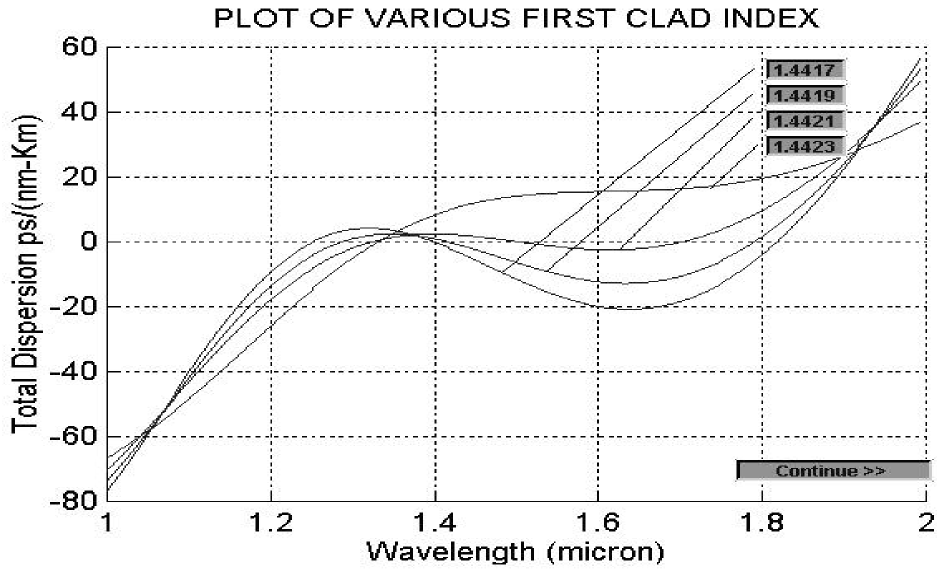

Figure 12 Dispersion factor versus wavelength with the first cladding refractive index of triple clad optical fibre as a parameter.

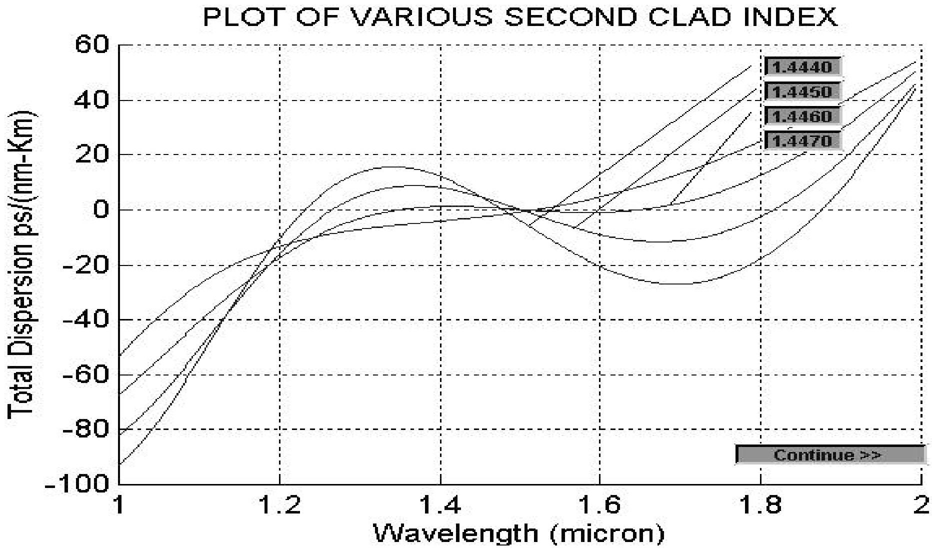

Figure 13 Total dispersion factor as a function of the second cladding refractive index of the triple clad optical fibre

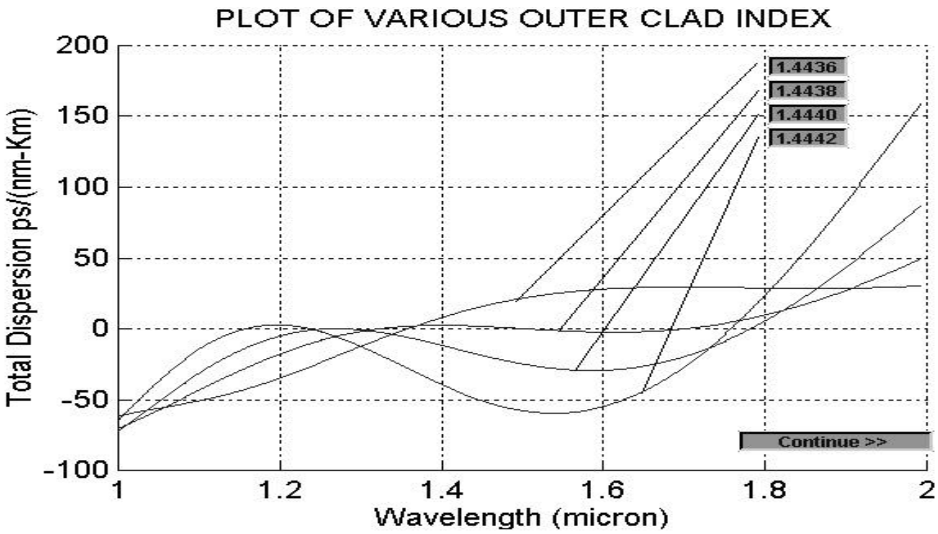

Figure 14 Total dispersion factor varies with variation of the outer cladding refractive index of the triple clad optical fibre.

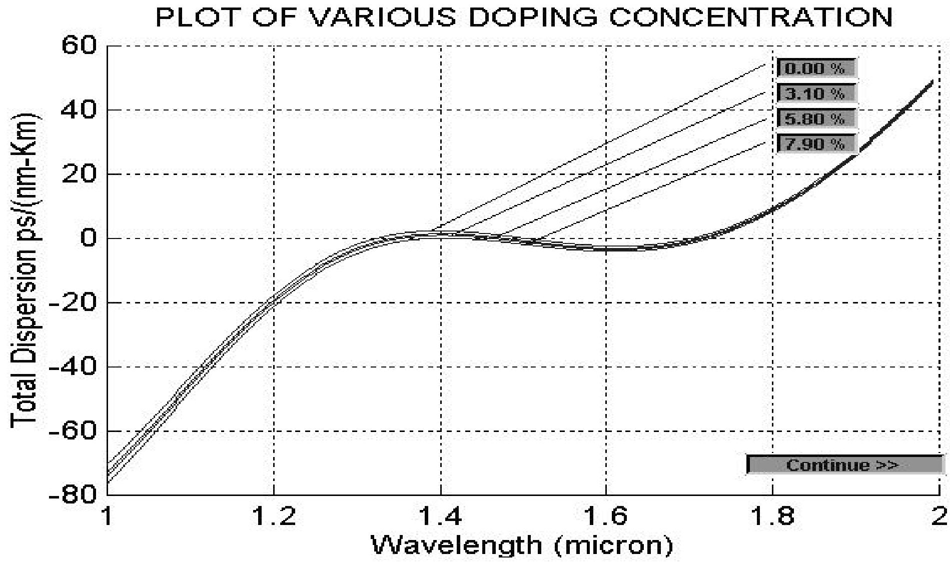

Figure 15 Total dispersion versus operating wavelength with doping concentration of the triple clad optical fibre as a parameter.

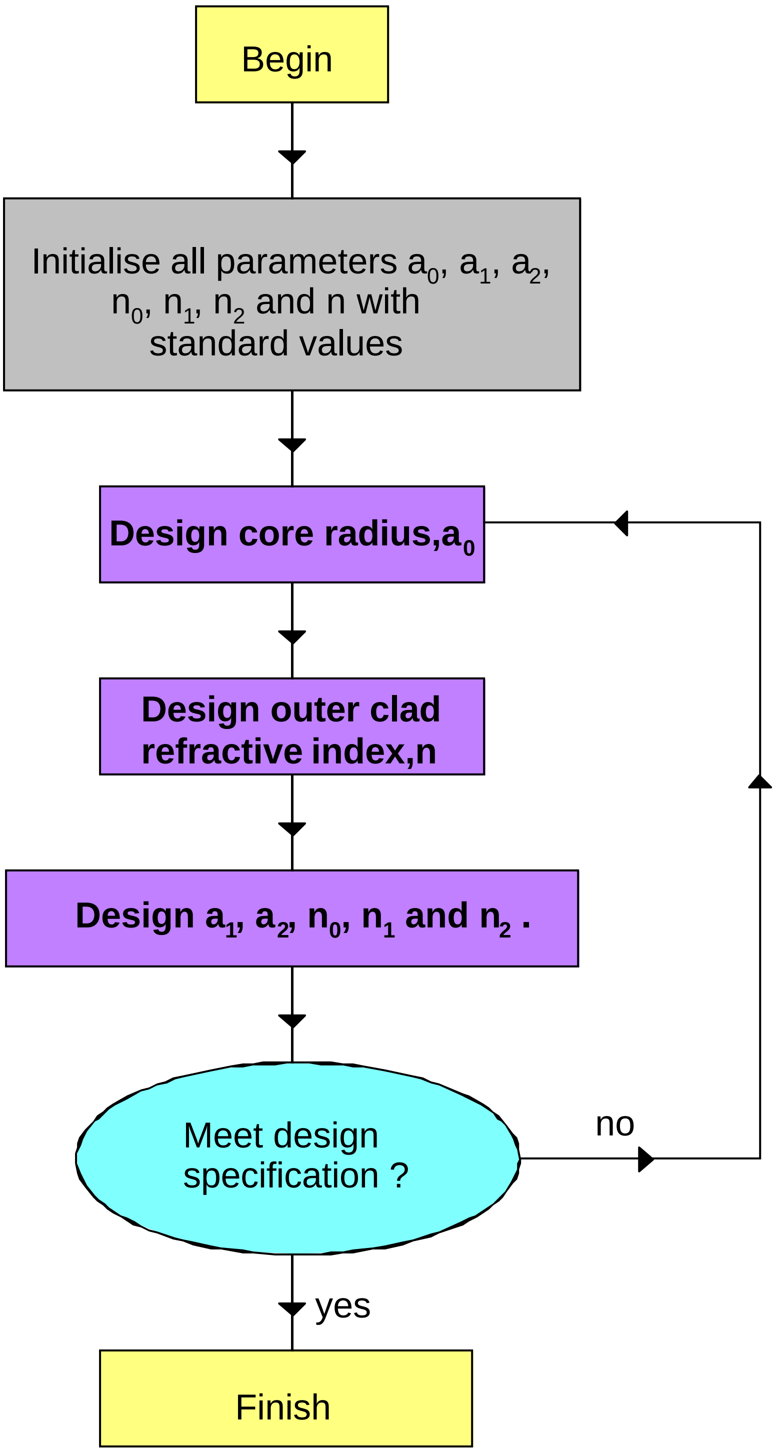

Figure 16 Flow chart of the design guidelines