Design of Multi-Layer Optical Fibers with Ring Refractive Index to Reduce Dispersion and Increase Bandwidth in Broadband Optical Networks

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Abstract— **The main goal in this paper is to design single-mode optical fibers for DWDM networks, which are used today in rapid communications. These networks require low dispersion in a wide range of wavelengths. So, in this paper, multi-layer optical fibers with low dispersion value and flat dispersion slope in wavelength range of (1.5-1.6μm) are designed, using optimization algorithms.**

Keywords- single-mode fiber; dispersion; dispersion slope; optimization algorithm.

I. INTRODUCTION

Triple-clad single-mode fibers have gain significant attention because of the perfect transmission properties that can be achieved by adjusting the multi-parameters [1–3]. A triple-clad fiber was firstly studied by Cozens and Boucouvalas as an optical coupler for sensing [4]. Dispersion curves for a particular coaxial structure were theoretically obtained with the resonance technique [5] and later by the solution of the transcendental equation [6]. In this paper, previous work reported in [5] is extended and the study is focused on the chromatic dispersion coefficient and the chromatic dispersion slope, and the design of triple-clad optical fibers with very low chromatic dispersion value and flat chromatic dispersion slope. A type of large effective area fibers with ring index profiles is proposed.

The effects made by the geometric parameters and optical parameters on the waveguide dispersion and cutoff characteristics of low order modes have been analyzed in detail. The calculated results indicate that the waveguide dispersion during single-mode propagation can be controlled by changing the optical and geometrical parameters. This means that it is possible to a obtain dispersion-flattened fiber with large effective-area along a region of wavelengths in WII type single-mode fibers [7]. The dispersion is optimized using a

Differential Evolution (DE) algorithm. Any similar structure can be optimized and controlled with this design. In section 2, a theoretical method to model the fiber structure and to obtain dispersion and dispersion slope in triple-clad fibers is investigated.

II. THEORETICAL MODELING OF FIBER STRUCTURE

Refractive index for WII structure is presented in Figure 1. Refractive index of each layer is as follows:

$$\begin{cases} n_1, \rightarrow 0 < r < a, \\ n_2, \rightarrow a < r < b, \\ n_3, \rightarrow b < r < c, \\ n_4, \rightarrow c < r, \end{cases} \qquad (1)$$

where r is the position vector of fiber radius.

Optical parameters are defined as:

$$R_1 = \frac{n_1 - n_3}{n_3 - n_2}, \qquad (2)$$

$$R_2 = \frac{n_2 - n_4}{n_3 - n_2}, \qquad (3)$$

$$\Delta = \frac{n_1^2 - n_4^2}{n_4^2} \approx \frac{n_1 - n_4}{n_4}, \qquad (4)$$

Geometric parameters are defined as follows [8]:

$$P = \frac{b}{c}, Q = \frac{a}{c} \qquad (5)$$
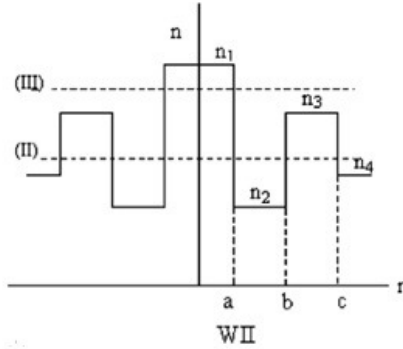

Fig. 1.   refractive index structure in the WII fiber[8].

Another parameter considered as a geometric parameter is the fiber core radius a, in the first layer.

Other parameters are as follows:

$$V = k_0 a \sqrt{n_1^2 - n_4^2}, \qquad (6)$$

$$B = \frac{\left(b/k_0\right)^2 - n_4^2}{n_1^2 - n_4^2} = 1 - \left(\frac{U_1}{V}\right)^2, \qquad (7)$$

where V is the normalized frequency, B is the normalized propagation constant [8] and r is the radial position. According to the effective refractive index given by $n_{eff} = \dfrac{\beta}{k_0}$ where β is the longitudinal propagation constant of guided mode and

k_0 is the wave number in free space, the structure of WII-type can be divided into two regions, which are shown in Figure 1. According to the wave equation, the boundary conditions of electromagnetic field and under the LP approximation, the characteristic equations in regions (II)–(III) can be as described in (14) and (15), and the parameters in these matrices are defined as follow:

$$U_1 = a\sqrt{k_0^2 n_1^2 - \beta^2}, \qquad (8)$$

$$U_2 = b\sqrt{\beta^2 - k_0^2 n_3^2}, \qquad (9)$$

$$U_3 = b\sqrt{k_0^2 n_3^2 - \beta^2}, \qquad (10)$$

$$W_3 = a\sqrt{\beta^2 - k_0^2 n_2^2}, \qquad (11)$$

$$W_4 = c\sqrt{\beta^2 - k_0^2 n_4^2}, \qquad (12)$$

$$W_3^{'} = \frac{P}{Q} W_3, U_2^{'} = \frac{1}{P} U_2, U_3^{'} = \frac{1}{P} U_3, \qquad (13)$$

$$\begin{bmatrix} J_m(U_1) & -I_m(W_3) & -K_m(W_3) & 0 & 0 & 0 \\ 0 & I_m(W_3^{'}) & K_m(W_3^{'}) & -J_m(U_3) & -Y_m(U_3) & 0 \\ 0 & 0 & 0 & J_m(U_3) & Y_m(U_3) & -K_m(W_4) \\ U_1 J_m^{'}(U_1) & -W_3 I_m^{'}(W_3) & -W_3 K_m^{'}(W_3) & 0 & 0 & 0 \\ 0 & W_3^{'} I_m^{'}(W_3^{'}) & W_3^{'} K_m^{'}(W_3^{'}) & -U_3 J_m^{'}(U_3) & -U_3 Y_m^{'}(U_3) & 0 \\ 0 & 0 & 0 & U_3^{'} J_m^{'}(U_3^{'}) & U_3^{'} Y_m^{'}(U_3^{'}) & -W_4 K_m^{'}(W_4) \end{bmatrix}$$

$$= 0,$$

$$\left(n_4 < n_{eff} < n_3, WII\right), \qquad (14)$$

$$
\begin{bmatrix}
J_m(U_1) & -I_m(W_3) & -K_m(W_3) & 0 & 0 & 0 \\
0 & I_m(W_3^{'}) & K_m(W_3^{'}) & -I_m(U_2) & -K_m(U_2) & 0 \\
0 & 0 & 0 & I_m(U_2^{'}) & K_m(U_2^{'}) & -K_m(W_4) \\
U_1 J_m^{'}(U_1) & -W_3 I_m^{'}(W_3) & -W_3 K_m^{'}(W_3) & 0 & 0 & 0 \\
0 & W_3^{'} I_m^{'}(W_3^{'}) & W_3^{'} K_m^{'}(W_3^{'}) & -U_2 I_m^{'}(U_2) & -U_2 K_m^{'}(U_2) & 0 \\
0 & 0 & 0 & U_2^{'} I_m^{'}(U_2^{'}) & U_2^{'} K_m^{'}(U_2^{'}) & -W_4 K_m^{'}(W_4)
\end{bmatrix}
$$

$$= 0,$$

$$\left(n_3 < n_{eff} < n_1, WII\right), \qquad (15)$$

where Y_m, K_m, J_m, I_m are the Bessel and modified Bessel functions. Dispersion and dispersion slope of mono-mode fiber are expressed in (17) and (18) respectively [9]:

$$D = -\frac{\lambda}{c}\frac{d^2 n_4}{d\lambda^2}\left[1 + \Delta\frac{d(VB)}{dV}\right] - \frac{n_4}{c}\frac{\Delta}{\lambda}V\frac{d^2(VB)}{dV^2}, \quad (16)$$

$$S = -\frac{\lambda}{c}\frac{d^3 n_4}{d\lambda^3}\left[1 + \Delta\frac{d(VB)}{dV}\right] - \frac{1}{c}\frac{d^2 n_4}{d\lambda^2}\left[1 + \Delta\frac{d(VB)}{dV}\right] +$$

$$\frac{n_4}{c}\left(\frac{\Delta}{\lambda^2}\right)V^2\frac{d^3(VB)}{dV^3} + 2\frac{N_4}{c}\left(\frac{\Delta}{\lambda^2}\right)V\frac{d^2(VB)}{dV^2} +$$

$$2\frac{\Delta}{c}\frac{d^2 N_4}{d\lambda^2}V\frac{d^2(VB)}{dV^2}, \qquad (17)$$

where $N_4 = n_4 - \lambda\frac{dn_4}{d\lambda}$, is the group index of outer cladding. N_4 and $\left(\frac{dn_4}{d\lambda}, \frac{d^2 n_4}{d\lambda^2}\right)$ represent the material dispersion of pure silica, which can be calculated by the Sellmeier formula [5]. In order to acquire the dispersion and dispersion slope of a mono-mode fiber, it is necessary to compute $\frac{d(VB)}{dV}$, $V\frac{d^2(VB)}{dV^2}$ and $V^2\frac{d^3(VB)}{dV^3}$, which represent the waveguide dispersion. Deducing from (7), we obtain [10]:

$$\frac{d(VB)}{dV} = 1 + \left(\frac{U_1}{V}\right)^2\left[1 - 2\left(\frac{U_1}{V}\right)\frac{dU_1}{dV}\right], \qquad (18)$$

$$V\frac{d^2(VB)}{dV^2} = -2\left(\frac{dU_1}{dV} - \frac{U_1}{V}\right)^2 - 2U_1\frac{d^2 U_1}{dV^2}, \qquad (19)$$

$$V^2\frac{d^3(VB)}{dV^3} = -6\left(\frac{dU_1}{dV} - \frac{U_1}{V}\right) - 2UV_1\frac{d^3 U_1}{dV^3} -$$

$$-6V\frac{d^2 U_1}{dV^2}\left(\frac{dU_1}{dV} - \frac{U_1}{V}\right), \qquad (20)$$

III. DESIGN AND OPTIMIZING DISPERSION AND DISPERSION SLOPE CURVES

In multi-layer fibers and specially WII fiber, dispersion depends on optical and geometrical parameters. Optimization algorithms are employed to design optical fibers with minimal dispersion and the desired optical and geometrical parameters. In this section, we employ DE optimization algorithm to design a fiber with low dispersion value and flat dispersion slope. A similar approach employing genetic algorithms to improve dispersion can be found in [8]. A DE algorithm cost function (CF) is considered in different ranges of wavelengths. A Gaussian function for the DE algorithm weight function is considered.

$$C.F = \sum_{\lambda_{\min}}^{\lambda_{\max}} W(\lambda) \times |Diapersion|, \qquad (22)$$

$$W(\lambda) = \exp\left(\frac{(\lambda - \lambda_0)^2}{2\sigma^2}\right), \qquad (23)$$
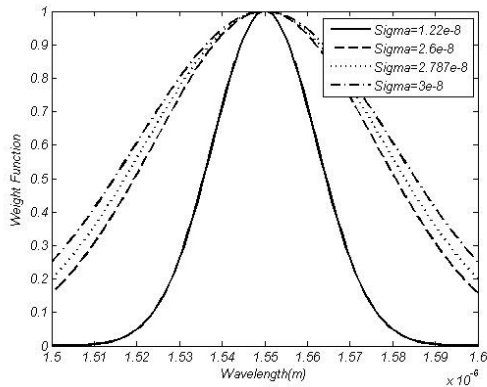
Fig. 2.   Gaussian weight function curve applied to the cost function.

Figure 2 represents the Gaussian weight function curve applied to the cost function. Due to the importance of $1.55\mu m$ in telecommunications networks, the wavelength

interval between $(1.5-1.6\mu m)$ was chosen, and it was attempted to shift the dispersion at this interval to zero dispersion wavelength.

IV. SIMULATIONS AND RESULTS

The dispersion optimization operations are chosen in $(1.5-1.6\mu m)$ wavelength range. DE algorithm results with $Sigma(1)=1.22e-8$, $Sigma(2)=1.6e-8$ and $Sigma(3)=2.787e=8$, with various optical and geometrical parameters are represented in Table 1. The dispersion and dispersion slope curves related to these tables are depicted in Figures 3 and 4 respectively.

TABLE I.   GEOMETRICAL AND OPTICAL PARAMETERS OBTAINED FROM THE DE ALGORITHM

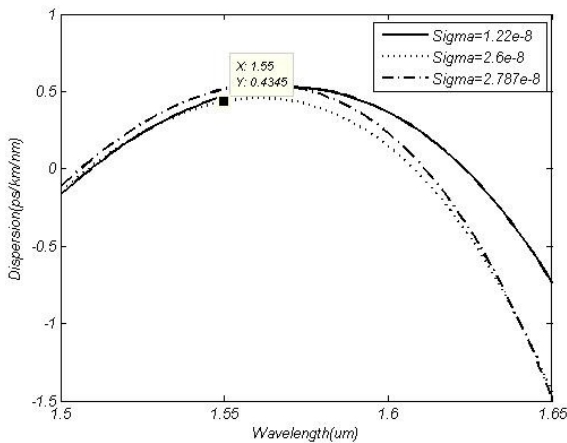| Parameters	Geometrical and optical parameters obtained from the DE algorithm with:		
	Sigma(1)=1.22e-8	Sigma(2)=1.26e-8	Sigma(3)=2.787e-8
R_1	3.15264670	3.09483016	3. 27005336
R_2	-0.92721549	-0.93197766	-0. 96152876
$a(\mu m)$	2.52132231	2.51136893	2. 51245195
Δ	55637852e-3	54855381e-3	53750754e-3
P	0.76817297	0.73308432	0. 72238260
Q	0.25397348	0.23099590	0. 22219703

Fig. 3.   Dispersion curves in different Sigmas, with shifted optimal wavelength.
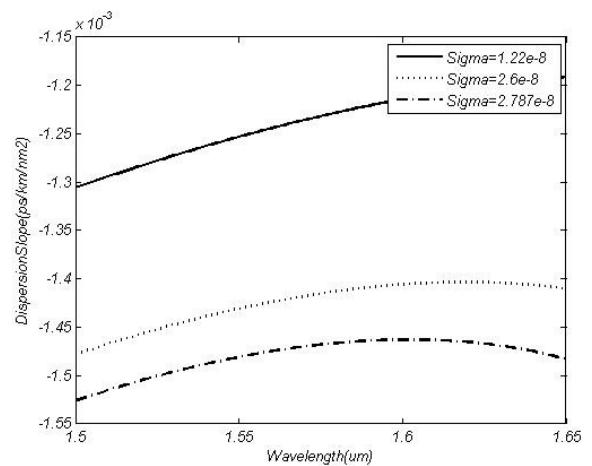

Fig. 4.   Dispersion slope curves in different Sigmas in correlation to table(1)

According to the results and dispersion curves obtained, we can easily see how dispersion wavelength is shifting towards zero dispersion wavelength. Also we can get minimum dispersion with desired sigma value and consequently shift the bandwidth to maximum desired value $(0.1\mu m)$ in this wavelength range.

Figures 5 and 6 show the dispersion and dispersion slope curves respectively for sigma=2.6e-8. According to the dispersion slope curve in wavelength range $(1.5-1.6\mu m)$, we can conclude that in this modeling, dispersion slope is almost flat.

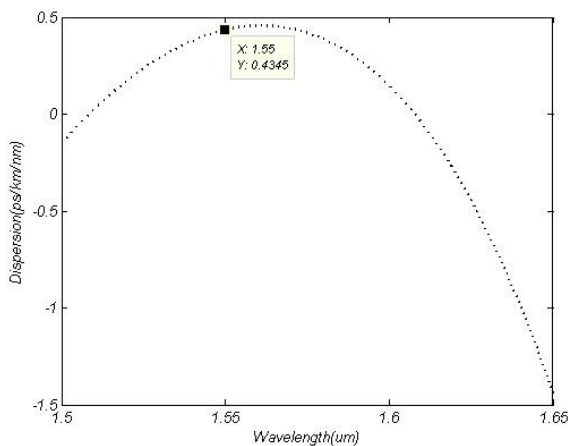Fig. 5.   Dispersion curve in sigma=2.6e-8.

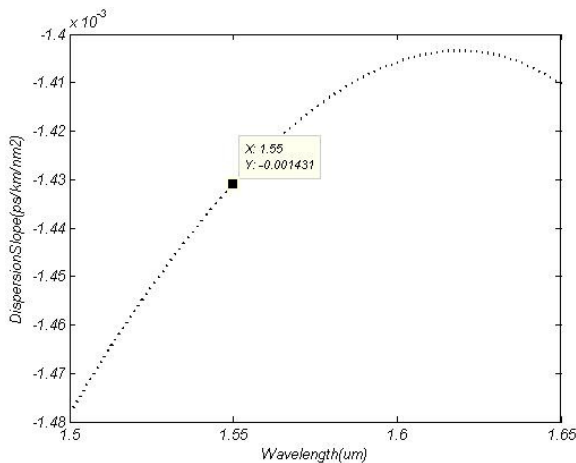Fig. 6.   Dispersion slope curve in sigma=2.6e-8.

Dispersion value in Figure 5 at $1.55\mu m$, equals to $0.4345\,ps/km/nm$ which is negligible to the increased bandwidth. It is also shown that the dispersion slope is flat in this bandwidth.

The results obtained here, compared with previous research [7-10] show remarkable improvement both in terms of dispersion and the amount of bandwidth obtained through optimization in DWDM networks.

V.   CONCLUSION

In this paper, we presented the design of multi-layer optical fibers with wide bandwidth, low dispersion and flat dispersion slope. Calculations show that with increasing distance between two points with zero dispersion, increased dispersion values are achieved. The main purpose of this paper is not to reduce the dispersion dramatically, but to optimize the bandwidth. Therefore, the optimization range of the wavelength is selected so as to increase the bandwidth and not to adversely effect the dispersion. This research, not only provides a novel fiber with flat dispersion, but also gives the basic principle behind the design of any fiber with any desired dispersion curve using appropriate optimization algorithms together with the desired cost function.

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