Full length article

Polarization dependent dispersion characteristics of high order modes in a cylindrical dual mode fiber with an arbitrary index profile

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Abstract

For a cylindrical dual mode optical fiber, dispersion characteristics of the high order polarization modes, TE\textsubscript{01}, TM\textsubscript{01}, and HE\textsubscript{31}, have been rigorously analyzed by solving the vectorial Maxwell equations numerically. The effects of the inner cladding index structure on the dispersion characteristics of the polarization modes are reported for the first time. In the matched cladding, the difference in chromatic dispersion, dispersion slope and modal delay among the polarization modes are found to increase for waveguide conditions optimized for a large negative dispersion. A new design of a cylindrical dual mode fiber with a depressed inner cladding that can intrinsically reduce the polarization dependence in the dispersion characteristics to improve the performance in dispersion compensation is proposed. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Optical fiber; Dispersion compensation; Optical waveguide design; Polarization

1. Introduction

In a large capacity wavelength division multiplexed (WDM) system, the optical fiber dispersion is one of the critical parameters that determine the capacity of data transmission. Relatively high value of chromatic dispersion in already installed 1.3 μm optimized conventional single mode fibers inhibits the high bit rate transmission in a long haul system operating in the wavelength region of erbium doped fiber amplifier (EDFA) gain band [1]. To overcome this dispersion penalty, various dispersion compensation techniques based on optical fibers [2–5] that provide negative dispersion and negative dispersion slope in the 1.5 μm region have been proposed.

The method of utilizing an intrinsically large negative dispersion value and a negative dispersion slope of excited modes in a dual mode fiber (DMF) was proposed by Poole [2]. The DMF is, in general, easier to fabricate with a relatively simple waveguide structure compared with a dispersion-compensating fiber (DCF) that operates in the fundamental mode by an elaborated waveguide design. Based on a scalar waveguide approximation, effects of the core refractive index profiles on the chromatic dispersion in DMF were reported [6]. Recently, Eguchi et al. [7] reported the results of calculation of waveguide dispersion of the TE\textsubscript{01} mode in a cylindrical DMF with various core index profiles using the finite element beam propagating method.

In previous studies, a DMF with a high relative index difference Δ over 2% operating near the cut-off condition was found to be most preferred for a large negative dispersion value. The same condition, however, will make the weakly guiding linearly polarized mode approximation
[8] no longer valid. And the fourfold degenerate LP11 mode will break into individual polarization modes, the TE01, the TM01 and the doubly degenerate HE21 modes that have their unique polarization states. Analogous to polarization mode dispersion in single mode fibers where the x and y linear polarization modes are concerned, dispersion properties in DMFs are affected by the polarization states of the high order modes. Detailed studies on the dispersion characteristics of the polarization modes for various waveguide parameters, however, have not been thoroughly studied yet.

The precise dispersion characteristics of individual modes in an optical fiber can be analyzed by solving the vectorial Maxwell equations including material dispersion of both core and cladding for a given refractive index profile. The exact analysis of a cylindrical waveguide of an arbitrary index profile has been reported by Paek et al. [9]. However, prior emphasis was on the dispersion characteristics of only the fundamental LP01 mode where the degeneracy of the mode is maintained. Here we are interested in the polarization dependent dispersion and the dispersion slope of the first excited modes in cylindrical DMFs with a high index difference where the degeneracy of the LP11 mode no longer holds.

In this study, we report for the first time, to the best knowledge of the authors, rigorous theoretical studies on polarization dependence in dispersion characteristics of TE01, TM01 and HE21 modes in cylindrical DMFs for various core and inner-cladding index profiles including the effect of material dispersion.

2. Maxwell’s equation in the vector form in a cylindrical dielectric waveguide

Vectorial Maxwell’s equations for a cylindrically symmetric optical fiber can be rigorously written as below [9], assuming a functional form for the bound propagating mode of \( A(r) \) exp \( \{ i \omega t - l \phi - k_r n_c r \} \),

\[
\frac{dA}{d\rho} = \frac{1}{\rho} \left[ \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} \right] \frac{d}{d\rho}. \tag{1}
\]

Here \( k_0 \) is the free space propagation constant, \( l \) the azimuthal mode number, \( n_c \), the effective index of the wave for the radial distance \( r \), the polar angle \( \phi \), and the longitudinal distance \( z \). \( A \) is a vector composed of tangential components of electromagnetic fields defined as below:

\[
A_1 = \rho^{-1} E_z, \quad A_2 = -i \rho^{-1} i H_\phi Z_0, \quad A_3 = \rho^{-1} i E_\phi, \quad A_4 = -i \rho^{-1} H_z Z_0, \tag{2}
\]

where \( Z_0 \) is the wave impedance of free space. The variable \( \rho \) is defined as \( k_0 r \).

The \( 4 \times 4 \) matrix \( A(\rho) \) can be written as:

\[
\begin{pmatrix}
0 & (n_c^2/\kappa) - 1 & 0 & -\ln_c/\kappa \\
\rho \kappa - l^2 & 0 & ln_c & 0 \\
0 & ln_c/\kappa & 0 & \rho^2 -(l^2/\kappa) \\
-\ln_c & 0 & n_c^2 - \kappa & 0
\end{pmatrix} \tag{3}
\]

In this matrix, \( \kappa = n^2 - 1 \) is the dielectric constant of the waveguide. In general, the refractive index, \( n \), is expected to change with frequency as well as along the radial distance. The frequency dependent refractive index profile was calculated based on a three term Sellmeir equation [10] assuming that the core and the cladding glass are composed of \( x GeO_2 - (1 - x)SiO_2 \) and \( x F - (1 - x)SiO_2 \), respectively. The concentration of GeO2 in the core and F in the cladding can be deduced from a given refractive index profile. The first order vector differential Eq. (1) was then solved numerically using the fourth order Runge–Kutta method. Using boundary conditions at the center and the core-cladding interface, the characteristic equation is obtained as:

\[
G(n_c) = \text{Det}[A_{ij}(\rho_c, n_c)] = 0, \tag{4}
\]

where index \( i \) specifies a particular vector component as in Eq. (2) and the index \( j \) specifies the pairs of homogeneous solutions to Eq. (1) such that \( j = 1, 2 \) are the core solution and \( j = 3, 4 \) the cladding solutions. Note that the characteristic equation is evaluated at the core-cladding interface \( \rho = \rho_c \). This is an implicit, transcendental equation and the zeros of the equation will give us the allowed values of effective index for each bound mode. The total dispersion of each mode is then obtained from the following relation:

\[
D_T = -\frac{\lambda}{c} \frac{d^2 n_c}{d\Lambda^2}. \tag{5}
\]

Note that the total chromatic dispersion includes the contribution of material dispersion of core and cladding glass as well as the waveguide dispersion.

3. Polarization dependence in dispersion characteristics of DMFs with the matched cladding

The index profiles of DMFs are schematically shown in Fig. 1 along with the waveguide parameters. Three types of refractive index profiles of the core were considered, step, parabolic, and triangular. The core refractive index structure is defined by \( \Delta^+ \), the raised relative index difference, and \( \alpha \), the core radius. The inner cladding structure is defined by \( \Delta^- \), the depressed relative index difference, and \( b \), the inner-cladding radius. Calculated total chromatic dispersion and its slope of DMFs with the matched cladding, \( \Delta^- = 0 \), are plotted as a function of the normal-
Fig. 1. The refractive index profile of a dual mode fiber. Here \( \Delta' \), \( \Delta'' \) are the relative index difference of the core and the inner cladding, respectively. The core radius and the inner cladding radius are \( a \) and \( b \), respectively.

Fig. 2. The total dispersion (a) and dispersion slope (b) of higher order polarization modes for various \( \alpha \)-profiles with matched cladding. The relative index difference, \( \Delta'' \) was varied from 0.4 to 2.5%. Note that the polarization dependence is rapidly increasing near the cut-off conditions with a high \( \Delta'' \) in both the chromatic dispersion and its slope.
Fig. 3. The polarization dependence in the chromatic dispersion of higher order polarization modes. Here $\Delta D_{\text{pol}}$ was defined as the maximum difference in the chromatic dispersion among the TE, TM, and the HE modes at a given $V$ number. and a high index difference are required. The same conditions, however, result in a large polarization dependence to significantly deteriorate the potential of DMF for dispersion compensation applications.

4. Polarization dependent modal delay for the matched claddings

The polarization mode dispersion (PMD) in the fundamental LP$_{01}$ mode is actually the modal delay between the two orthogonal linear polarizations given in units of ps/km [12,13]. Slight difference in propagation constants of the two polarization states in a single mode fiber primarily due to geometric ellipticity of the waveguide will break the degeneracy of the LP$_{01}$ or the HE$_{21}$ mode into two polarization modes. And the differences in the time delay between the modes, as defined below, results in PMD of $\sim 1$ ps/km for the core ellipticity of 1% [16]:

$$\Delta \tau = \frac{\Delta n_2}{c} - \lambda \frac{d \Delta n_2}{d \lambda}, \quad (6)$$

Here $\Delta n_2$ is the difference in the effective indices of two orthogonal polarization modes and $L$ is the fiber length.

In cylindrical DMFs, the degeneracy of the LP$_{11}$ mode is removed intrinsically by the high index difference even without external geometric ellipticity. In order to analyze the time delay between the polarization modes, the following parameters were introduced for the TE$_{01}$, the TM$_{01}$, and the HE$_{21}$ modes:

$$\frac{\Delta \tau_1}{L} = \frac{n_{2e}^{\text{TE}} - n_{2e}^{\text{TM}}}{c} - \lambda \frac{d (n_{2e}^{\text{TE}} - n_{2e}^{\text{TM}})}{d \lambda}, \quad (7)$$

$$\frac{\Delta \tau_2}{L} = \frac{n_{2e}^{\text{TE}} - n_{2e}^{\text{HE}}}{c} - \lambda \frac{d (n_{2e}^{\text{TE}} - n_{2e}^{\text{HE}})}{d \lambda}. \quad (8)$$

Here $\Delta \tau_1/L$ represents the modal delay between the TE$_{01}$ mode and the TM$_{01}$ mode while $\Delta \tau_2/L$ represents the modal delay between the TE$_{01}$ mode and the HE$_{21}$ mode. The effective indices are labeled as $n_{2e}^{\text{TE}}$, $n_{2e}^{\text{TM}}$, $n_{2e}^{\text{HE}}$ for the TE$_{01}$, the TM$_{01}$, and the HE$_{21}$ modes, respectively. Calculation of the modal delay was done using vectorial Maxwell’s equation solver for various core index profiles with the matched cladding and the results are shown in

Fig. 4. The modal delays as a function of $V$ number for various $\Delta \tau$ in a dual mode fiber with matched cladding and (a) step core index, (b) parabolic core index, and (c) triangular core index. Here $\Delta \tau_1/L$ is the modal delay between the TE$_{01}$ and the TM$_{01}$ modes, while $\Delta \tau_2/L$ is between the TE$_{01}$ and the HE$_{21}$ modes.
Fig. 4. In the figure, modal delays show a similar behavior as dispersion and dispersion slope in the previous section. DMFs with a low index difference show modal delays of few tens of ps/km when V number is far away from the cut-off condition while a high Δv results in large modal delays near the cut-off. Especially for a step index Δv of 2.5%, Δτf/L and Δτs/L show modal delay of ~7 and ~3 ns/km, respectively, near V = 2.5. Note that these time delays are about three orders of magnitude larger than the PMD of the LP01 mode in a conventional single mode fiber [14, 15]. The modal delay Δτf/L between the TE01 and TM01 is found to change its sign depending on the core profile such that the values in the triangular and parabolic cores are ~1.0 and ~0.75 ns/km, respectively. From the results in Figs. 2 and 3, it is found that the DMFs optimized for a large negative dispersion, high Δv and near cut-off, will generate a large polarization dependent time delay of a few ns/km which significantly limits the data rate of incoming optical signals.

Through the analysis of polarization dependence in dispersion characteristics of DMFs of the matched cladding, either a polarization filter or a scrambler was found to be indispensable for practical applications in dispersion compensator.

5. Polarization dependence in dispersion characteristics of DMFs with a depressed cladding

It has been well understood that the dispersion of guided modes in optical fibers is very sensitive to the cladding index profile as well as the α-profile in the core. And a W-shaped fiber profile [17] with a narrow depressed inner cladding is widely used to control the waveguide dispersion of the fundamental mode in various types of single mode fibers such as dispersion shifted fibers, dispersion flattened fibers [18] and dispersion compensating fibers [19]. In fact, two requirements for dispersion compensating single mode fiber, the negative dispersion slope and the negative dispersion in the 1.5 μm region can be simultaneously achieved only by appropriate design of the cladding index profile [20]. The depressed inner cladding structure can also change the cut-off conditions of the guided modes such that with a proper inner cladding index profile a few modes could be selectively guided [21]. Nevertheless, the effects of cladding structure in DMFs have been neglected and only the core profiles have been studied assuming the matched cladding structure in previous works.

In this study, the effects of depressed inner cladding on the dispersion characteristics in DMFs are thoroughly analyzed. The inner cladding structure is shown in Fig. 1, which is characterized by the depth Δv, and the width b. Index depression was assumed to be achieved by F doping in silica. Due to the largest negative dispersion among α-profiles, analysis on the inner cladding was carried out only for step index core profiles. In Fig. 5, the chromatic dispersion of a step index core with various inner cladding indices was calculated for the b/a ratio, the ratio of inner cladding radius to that of the core, of 2.5, 5.0 and 7.0. In the depressed inner cladding structure, the negative dispersion increased by twofold to fourfold compared with the matched cladding case of the same index difference. The

Fig. 5. The chromatic dispersion of high order polarization modes in dual mode fibers with the step index core and depressed inner cladding structures. The dispersion values are plotted as a function of Δv, for b/a ratio of 2.5, 5.0 and 7.5 as shown in (a), (b) and (c), respectively. Note that the dispersion was evaluated for the cut-off condition of each mode such that the effective index is the same as the refractive index of pure SiO2. The arrows in (b) and (c) indicate the conditions for which only TE01 and TM01 modes are guided with the same chromatic dispersion value. The waveguide parameters in these cases are summarized in Table 1.
deeper the inner cladding, with more negative $\Delta^-$, the larger negative dispersion value is achieved. The width of inner cladding also affects the dispersion for the same $\Delta^-$ such that a narrower inner cladding, with a smaller value of $b/a$, produced a larger negative dispersion. These sensitive dependence of dispersion properties of polarization modes on the inner cladding structure could be understood by the waveguide dispersion as explained by Jeunhomme [22]. At a short wavelength or at a high $V$ number, the envelopes of the modes, TE$_{01}$, TM$_{01}$, and HE$_{21}$ are confining to the core region and behave as if the depressed inner cladding extends to infinity. When the wavelength increases or $V$ number decreases, the envelope of the modes quickly extends over the depressed inner cladding and the significant portion of envelope tail is under the influence of outer cladding of a higher index. This behavior will sharply change the curvature of the effective indices versus wavelength, or $V$ number curves of polarization modes inducing strong waveguide dispersion.

Compared with the matched cladding cases, DMFs with the depressed inner cladding could show very different cut-off conditions for higher order polarization modes. The cut-off of a mode is defined as the condition at which its effective index is the same as that of outer cladding or pure SiO$_2$ glass following the convention [21]. It is known that the cut-off conditions of TE$_{01}$ and TM$_{01}$ modes can be separated from that of the HE$_{21}$ mode even in a matched step index of very high $\Delta^-$ exceeding 50%, close to that of air to glass index difference [23]. However, such a high $\Delta^-$ referenced to SiO$_2$ is not realistic in the present technology for low loss optical fibers. Within achievable range of $\Delta^-$ using GeO$_2$ doping, our analysis results show that in DMFs with matched cladding all of the first excited modes show one and identical cut-off condition within our calculation error as shown in Fig. 2. In a depressed inner cladding case, however, the cut-off conditions for the modes were found significantly altered. The HE$_{21}$ mode has a different cut-off condition, while the TE$_{01}$ and the TM$_{01}$ modes share a common cut-off condition. This anomalous cut-off behavior in the double cladding structure is consistent with the previously reported results of Monerie [21], which was in the LP approximation based on scalar filed theory.

In Fig. 5, chromatic dispersion of DMFs of the depressed inner cladding is shown with different cut-off conditions for higher order polarization modes. In the

![Fig. 6](image-url)

Fig. 6. The modal delays between the higher order polarization modes in dual mode fibers with the step index core and the depressed inner cladding structure. The modal delays are plotted as a function of $\Delta^-$, for the core index $\Delta^+$ of 0.4, 0.8, 1.3 and 2.5% as shown in (a), (b), (c) and (d), respectively. The arrows in (d) are for the DMF of type 1 and type 2 whose waveguides are defined in Table 1.
In order to utilize DMF as a dispersion compensator, a large negative chromatic dispersion value is required. But the optimized waveguide condition for a large negative dispersion in a cylindrical DMF will result in high polarization dependence in chromatic dispersion and large modal delays between the higher order modes. The propagation of the incident pulse in the LP_{01} mode through a mode converter and a DMF with matched cladding is schematically shown in Fig. 7(a). After conversion into the LP_{11} mode, the incident pulse could excite the polarization modes TE_{01}, TM_{01} and HE_{21} defined by the DMF structure. The modes will propagate in the DMF with different propagation constants and different pulse widths due to polarization dependent dispersion. Assuming negligible mode coupling, the pulse in the TE_{01} mode will lag behind TM_{01} and the leading pulse will be in the HE_{21} mode in the step index core. Note the polarization dependence in DMF results in the separation of modes in both the time and the space domain. Even though the negative dispersion of each higher order mode could be large, polarization mode dispersion, especially the modal delay, could make the overall pulse width after DMFs longer than that of the incident pulse. Effective dispersion compensation is, thus, permitted only if polarization dependence could be overcome by additional polarization controlling devices.

In a cylindrical DMF with matched cladding structure, an effort to diminish the polarization dependence was previously attempted by introducing geometric ellipticity in the core [24]. However, the technique was basically to separate the linear combination of the polarization modes TE_{01} + HE_{21} from TM_{01} + HE_{21} or vice versa depending on the lobe direction with respect to the major axis of the elliptical core fiber. Note that the difference in dispersion behavior is much larger between HE_{21} and TE_{01} (or TM_{01}) than that between TE_{01} and TM_{01} as shown in Fig. 2. Especially, the modal delay \( \Delta \gamma/L \) between the HE_{21} mode and the TM_{01} mode (or TE_{01}) is about three or four times larger than \( \Delta \gamma/L \) between the TE_{01} and the TM_{01} mode, see Fig. 3. In addition to the elliptical core design, a polarization rotation had to be added in the middle of the DMF to remove the effects of the relatively long modal delay.

In the depressed cladding structure, however, it is found that only the TE_{01} and the TM_{01} mode could be made guided with the same chromatic dispersion, see the arrows in Fig. 5(b) and (c). This approach could be more efficient compared with previous elliptical core since the modal delay is defined only between the TE_{01} and the TM_{01} which is intrinsically shorter than that between the HE_{21} mode. And due to cylindrical symmetry of the field structures, TE_{01} and TM_{01} modes in DMFs with the depressed cladding would have lower bend sensitivity than the elliptical core fibers whose lobe directions are very sensitive to the bend. In Fig. 7(b), the mode propagation along a depressed cladding DMF is shown schematically. Note that the HE_{21} mode is no longer guided and the pulse width of the TE_{01} mode and the TM_{01} mode are identical due to degenerate chromatic dispersion. However, the
The modal delay between the two modes, $\Delta \tau_1$, still exists and it will cast a limit to the data rate of incident optical pulses. In general, the modal delay and the data rate of optical signals should satisfy the inequality below with appropriate proportional constants depending on the format of coding [25],

$$\Delta \tau < T_B = \frac{1}{DR} \quad (9)$$

where $T_B$ is the bit period in second and DR is the data rate in bit per second (bps). In order to evaluate the performance of the proposed DMF with depressed cladding structure as a dispersion compensator, both the net amount of dispersion compensation and the permitted maximum data rate should be simultaneously considered for a given length of the DMF. As shown by the arrows in Fig. 5(b) and (c), the TE<sub>01</sub> and the TM<sub>01</sub> mode can have the same large negative chromatic dispersion value while the HE<sub>21</sub> mode is no longer guided. But the modal delays under the same condition as indicated by the arrows in Fig. 6(d) will restrict the maximum data rate. The waveguide parameters, chromatic dispersion values, and the modal delays for the proposed cases are summarized in Table 1. For two proposed depressed inner cladding structures as in Table 1, the amount of dispersion compensation (ps/nm) and the maximum data rate (Gbps) are plotted as a function of the DMF length in Fig. 8. It is found that a long DMF fiber will result in a large amount of dispersion compensation but the permitted data rate will significantly decrease. For instance, for the data rate of 2.5 Gbps, it is found in Fig. 8(a) that the DMF length should be kept below $\sim 150$ m and the net amount of dispersion compensation is only about $70$ ps/nm. Despite the intrinsically large negative dispersion of DMF, the modal delay between the TE<sub>01</sub> and TM<sub>01</sub> mode is found to be the most significant limiting factor for practical application of the depressed inner cladding DMF in high speed optical communication systems.

In order to utilize DMFs as a dispersion compensator transparent to a high data rate, over 2.5 Gbps, for instance, it is imperative to reduce the modal delays among higher order modes. Previously reported method was to insert an external polarization-rotating device in the middle of elliptical core DMF [11]. Another technique could be devel-
Fig. 8. The maximum data rate and the amount of dispersion compensation as a function of fiber length. Here two dual mode fibers, type 1 and 2, whose waveguide parameters and dispersion characteristics are given in Table 1, are considered in (a) and (b), respectively.

oped using two segments of DMFs that have modal delays of opposite signs. As shown in Fig. 4(b) and (c), the modal delay between the TE$_{01}$ and the TM$_{01}$ modes shows a negative value. Especially for the triangular core DMF of $\Delta' = 2.5\%$, the modal delay is below $-1.0$ ns/km for the matched cladding structure. Concatenating the proposed DMFs of type 1 or 2 with a triangular core DMF of a negative modal delay, the net modal delay through the whole fiber can be reduced significantly. A further research on waveguide parameters for the concatenated DMF for polarization independent dispersion compensators is being pursued.

The modal delays among the polarization modes in DMFs, on the whole, could be efficiently utilized in other applications such as spatial mode converters. For the case of high $\Delta'$ step index fiber with matched cladding structure, the modal delays between the modes could exceed a few nanoseconds and polarization modes could be chosen selectively in time domain by a switch of moderate speed ($<1$ ns). Polarization mode filtering could be achieved in a continuous manner by proper synchronization of switching at the output to the repetition rate of incident incoming pulse train. Conversion of a Gaussian-like pulse into a ring type pulse such as TE$_{01}$ or other excited modes could find useful applications especially in mode shaping in a low repetition rate high power solid state laser system. Actually the configuration shown in Fig. 7(a) and (b) could be used as the LP$_{11}$ to TE$_{01}$ mode (or any other excited modes) converter, with a proper synchronization of a switch at the output of the DMF. The TE$_{01}$ output pulse, for instance, can be fed into another cascaded DMF for pulse compression and the dispersion will be determined by only the TE$_{01}$ mode without polarization dependence. This kind of pulse compression still could be effective for high peak power Q-switched pulses of a relatively low repetition rate from a solid state laser. The ring shaped spatial distribution and a large mode field area of the TE$_{01}$ mode could lower the nonlinear effects compared with Gaussian type modes.

7. Conclusion

We have thoroughly analyzed the polarization dependence of dispersion properties of higher order polarization modes in a cylindrical dual mode fiber of arbitrary index. The dispersion properties of the modes were found to be very sensitive to the inner cladding structure as well as the core index. Dispersion compensation based on DMFs at a high data rate was found to be strongly affected by the polarization dependence of the chromatic dispersion and the modal delays among the polarization modes. The polarization dependence could be alleviated in a cylindrical core fiber with a depressed inner cladding structure guiding only TE$_{01}$ and TM$_{01}$ modes. Dispersion compensators based on concatenated dual mode fibers that have opposite sign for modal delay between TE$_{01}$ and TM$_{01}$ modes could have potential for data rate transparent dispersion compensation.

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