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Performance study of different step index multi-clad fiber for broadband application

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ABSTRACT

In this paper, the analytical study of the performance characteristics like group delay, effective mode field diameter (MFD) and dispersion curves of an optical fiber having various cladding layers are presented. The proposed six structures of optical fiber have three parts, namely core with highest refractive index dielectric material, inner claddings and outer cladding. The group delay, MFD and dispersion depend on the number of cladding in optical fiber. The zero dispersion wavelengths vary with number of cladding increases or decreases. The guided modes and propagation wave vectors can be evaluated by using a determinant which is constructed by the boundary matched method. The cutoff conditions of modes for varying number of inner claddings are compared. The analysis shows that the propagation property can be controlled of an optical fiber by increasing the number of inner claddings and diameter of the core. These claddings provide a degree of freedom to control the modes and other characteristics of the fiber.

1. Introduction

Today, Optical fibers have emerged to play a key role in making possible the extraordinary growth in world-wide communications and many engineering applications that has occurred in the last 25 years. There are many desirable properties of optical fibers for carrying this information. They have enormous information-carrying capacity, are low cost, and possess immunity from the many disturbances. It is well known the propagation of light in optical fiber are highly depend on the geometry of fiber, the dielectric material used and the width of the core and cladding. Hence there are a number of cross-sections [1–3] and the compositions [4–6] of the core/clad through the lightwave can propagate and controlled are studied. A special type of refractive index profile of optical fiber known as a W-fiber depressed cladding gives some desirable properties and unique characteristics distinguish to standard optical fibers [7]. A properly designed W-fiber supports a fundamental mode with a finite cut-off wavelength [8–10]. The doubly clad W-profile fiber is currently one of the most noticeable dispersion-flattened fibers [11–13]. The waveguide dispersion for such kind of optical fibers is strongly influenced by the geometrical and optical parameters [14]. In order to achieve more perfect dispersion-flattened and-shifted characteristics, and to achieve the single-mode propagation, the size of the core radius must be reduced [15]. The advantages of triple-clad fibers are that more perfect dispersion-flattened and shifted characteristics can be achieved by adjusting some parameters, which can overcome the difficulties that doubly clad *W*-profile optical fibers encounter [16].

Triple-clad single-mode fibers have been closely paid attention because the perfect transmission properties can be achieved by adjusting the cladding parameters. Cozens and Boucouvalas first studied a triple-clad fiber as an optical coupler for sensing [17]. Dispersion curves for a particular coaxial structure were theoretically obtained with the resonance technique [18] and later by solution of the transcendental equation [19]. A biconical-taper coaxial coupler and filter was reported [20]. The transmission characteristics of triple-clad multi-mode fibers with different refractive index profiles, modal dispersion and field distribution during the multi-mode propagation were studied in detail [21], but the corresponding properties during single-mode propagation were not discussed. The studied results indicated that the waveguide dispersion characteristics of these kinds of fibers were influenced by the optical parameter, but the corresponding chromatic dispersion and higher-order dispersion were not studied because the characteristic equations are so complex that it is difficult to examine the chromatic dispersion coefficient and chromatic dispersion slope.

In this paper, we extended work reported in [22,23] and focused our study on the chromatic dispersion, dispersion slope, and MFD established successfully. Use theoretical approach to calculate the

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chromatic dispersion and MFD. The cutoff condition in a doubly clad fiber first and then we increase the number of inner cladding, two to three and then three to five and five to seven compare the cut-off condition for single mode propagation among these three fibers [9] Triple-clad [24], five-clad, six-clad [25] and seven-clad fibers. The fiber characteristic group delay, chromatic dispersion and MFD plotted together for double-seven clad fibers. Therefore, by adjusting each parameter reasonably, the chromatic dispersion, group delay, MFD and guided modes can easily be optimized or match with our demands. The objective of this work is to observe the effect of number of cladding on the characteristic parameters of multi-clad optical fiber for different communication applications.

The papers are organized as follows; in Section 2, the derivation of the characteristic equations of group delay, MFD and dispersion. The calculations of a characteristic dispersion relation using weak guidance condition are presented. In Section 3, numerical results and discussion are given. Finally, the paper ends with a conclusion given in Section 4.

2. Theoretical and mathematical analysis

2.1. Group delay

Let us consider a data signal propagating in a single mode fiber of length L. Each spectral component of the signal undergoes a time delay t_g. the group delay per unit length is τ_g obtained as

$$\tau_g = \frac{t_g}{L} = \frac{1}{v_g} = \frac{1}{c}\frac{\mathrm{d}B}{\mathrm{d}k_0} = \frac{-\lambda^2 \mathrm{d}\beta}{2\pi c \mathrm{d}\lambda} \tag{1}$$

where $v_g = \left(\mathrm{d}\beta/\mathrm{d}\omega\right)^{-1} = c\left(\mathrm{d}B/\mathrm{d}k_0\right)$ is the group velocity, $k_0 = 2\pi/\lambda$ is the free-space wave number, and c is the velocity of light in free space. Spectral components travel at different speeds and experience different time delays. The pulse spreading arising from group delay variations and the root-mean-square spectral width of the optical source is σ_λ, then the total delay difference is given by

$$\delta\tau = \frac{\mathrm{d}t_g}{\mathrm{d}\lambda}\sigma_\lambda L \tag{2}$$

The amount of pulse spread per unit length of fiber and per unit spectral width of light source is defined as dispersion.

2.2. Mode field diameter

The MFD is an important parameter related to the optical field distribution in the fiber. It has been shown that MFD provides useful information about the cabling performances, such as possible joint, macro bending, and micro bending losses. In an optical signal, not all the light travels through the core of the fiber. The optical power is distributed between the core and the cladding. The "Mode Field" represents the distribution of light through the core and cladding of a particular fiber. The near-field Mode Field Diameter (n-MFD). It is the diameter at which the near field power falls to $1/e^2$ its maximum value [28]. It can be written as

$$d_n = 2\sqrt{2}\left(\frac{\int_0^\infty E^2(r)r^3\mathrm{d}r}{\int_0^\infty E^2(r)r\mathrm{d}r}\right)^{1/2} \tag{3}$$

where $E(r)$ is the optical mode field distribution.

The far-field Mode Field Diameter (f-MFD). It is the diameter at which the far field power falls to $1/e^2$ of its maximum value. It can be written as

$$d_f = 2\sqrt{2}\left(\frac{\int_\infty{}^0 E^2(r)r\mathrm{d}r}{\int_\infty{}^0 [E'(r)]^2 r\mathrm{d}r}\right)^{1/2} \tag{4}$$

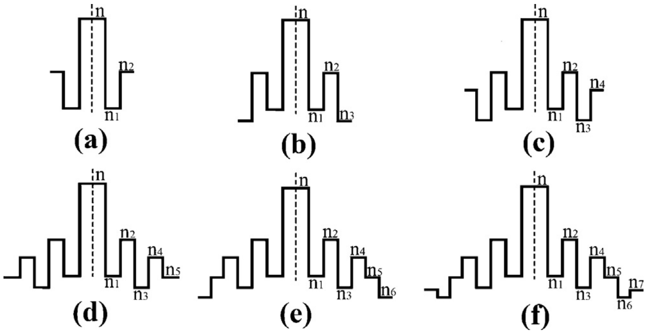

Fig. 1. The index of refraction profile for (a) double clad, (b) triple clad, (c) four clad, (d) five clad, (e) six clad and (f) seven clad.

The effective Mode Field Diameter (eff-MFD) written as

$$d_{\mathrm{eff}} = \frac{2\sqrt{2}\int E_i^4 r\mathrm{d}r}{\left[\int E_i^4 r\mathrm{d}r\right]^{1/2}} = \frac{2}{\pi}\sqrt{A_{\mathrm{eff}}} \tag{5}$$

where A_{eff} is the effective mode area.

2.3. Analysis of chromatic dispersion

Hence, we can say that pulse broadening per unit length for unit spectral width is called dispersion. The total dispersion is the total effect of material and waveguide dispersion. These dispersions are together is called the chromatic dispersion.

$$\text{Chromatic dispersion} = D_{\mathrm{mat}} + D_{\mathrm{wg}}$$

where D_{mat} depends upon the material taken for the construction of the optical fiber. D_{wg} is the parameter that depends upon the structure of the fiber According to the definitions of chromatic dispersion coefficient D [26], the expressions of chromatic dispersion coefficient D and its slope S can be obtained as follows:

$$D = -\frac{\lambda}{C}\frac{d^2}{\mathrm{d}\lambda^2}\left[1 + \Delta\frac{\mathrm{d}BV}{\mathrm{d}V}\right] - \frac{N_4}{c}\frac{\Delta}{\lambda}V\frac{d^2(BV)}{\mathrm{d}V^2} \tag{6}$$

$$\begin{aligned} S = {} & -\frac{\lambda}{C}\frac{d^2}{\mathrm{d}\lambda^3}\left[1 + \Delta\frac{\mathrm{d}BV}{\mathrm{d}V}\right] - \frac{1}{c}\frac{d^2 n_4}{\mathrm{d}\lambda^2}\left[1 + \Delta\frac{\mathrm{d}BV}{\mathrm{d}V}\right] \\ & + \frac{N_4}{c}\frac{\Delta}{\lambda^4}V^2\frac{d^3(BV)}{\mathrm{d}V^3} \\ & + 2\frac{N_4}{c}\frac{\Delta}{\lambda^2}V\frac{d^3(BV)}{\mathrm{d}V^2} \end{aligned} \tag{7}$$

where $N_4 = n_4 - \lambda \mathrm{d}n_4/\mathrm{d}\lambda$ is the group index of the outer cladding and $d^m n_4/\mathrm{d}\lambda^m$ $(m = 1,2,3)$ can be calculated by Sellmeier formula [27]. In current section the modal analysis based on boundary matching technique for the proposed structure illustrated in Fig. 1, is presented. The refractive indices of the structure are given as

$$n(r) = \begin{cases} n_1, & 0 < r < a, \\ n_2, & 0 < r < b, \\ n_3, & 0 < r < c, \\ n_4, & 0 < r < d, \\ n_5, & 0 < r < e, \\ n_6, & r > e, \end{cases} \tag{8}$$

The radius of the core, first-cladding, second cladding, third cladding, fourth cladding, fifth cladding, six cladding, and seven cladding are, respectively, given by a, b, c, d, e and f their corresponding cladding width are given as $d_1, d_2, d_3, d_4, d_5, d_6$. In this proposed structure the radius and refractive index of core control modes,