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# Dispersion characteristics of novel class multi-clad dispersion shifted hollow core fibers for WDM optical systems

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The design and analysis of multiple-clad hollow core dispersion-shifted fibers have been presented in this paper. Fiber profiles have been designed consisting of a central core that is hollow and outer cladding is silica. The novel refractive index profile has multi-clad for enhanced optical characteristics. Optical fibers with two or more claddings are required for dispersion shifting, dispersion flattening, and other specialized applications. Thus, the hollow core fiber shows the zero dispersion at 1550 nm wavelength. These hollow core fibers have potential application in WDM optical systems.

**Keywords**: Multi-clad fiber, Hollow core fiber, Dispersion shifted design, Dispersion, Confinement

## 1 Introduction

In this paper, we have introduced the hollow core multi-clad optical fibers [HCMF]. A simple analytical study of their characteristics has been performed. The optical fibers with two or more claddings are required for dispersion shifting, dispersion flattening, and other specialized applications. The geometry considered here is limited to a four-layer cylindrical dielectric structure, consisting of a core and three claddings. A unified formulation is developed which is applicable to all possible multi-clad fibers with step-index profiles. Thus, the formulation presented in this paper is applicable to optical fibers with two and three claddings. A multi-clad fiber was initially studied by Cozens and Boucouvalas as an optical coupler for sensing[1]. Dispersion curves for a particular coaxial structure were theoretically obtained with the resonance technique[2,3] and later by solution of the transcendental equation[4]. The transmission characteristics of types of multi-clad optical fibers with different refractive index profiles[5-7], the modal dispersion and field distribution during the single-mode propagation were studied in detail[8]. The advantages of multi-clad fibers are that more perfect dispersion-flattened and dispersion shifted characteristics can be achieved by adjusting some parameters, which can overcome the difficulties that W-profile optical fibers encounter[9-11]. We use theoretical approach to calculate the chromatic dispersion and mode cutoff conditions. First the cutoff condition is calculated in a doubly clad fiber then we increase the number of inner cladding, two to three then compare the cut-off condition for single mode propagation among these three fibers[12]. Dispersion shifted fiber[12-15], the fiber characteristic chromatic dispersion, modes and propagation constant are then plotted together for dispersion shifted, dispersion flatted and dispersion compensating fibers. Therefore, by adjusting parameter reasonably, the chromatic dispersion and guided modes can easily be optimized or match with our demands. The objective of this paper is to observe the effect of change in refractive index profile on the mode and dispersion of triple-clad optical fiber for different communication applications.

In this paper, we have focused our study on the dispersion, dispersion slope and power confinement properly in multi-clad fibers. Theoretical approach has been used to calculate the dispersion and modes. The cutoff condition is calculated first in a multi-clad fiber and then we change the refractive index profile of solid and hollow core, following the two different structure while compare the dispersion and zero dispersion wavelength.

## 2 Theory of Hollow Core Multi Clad Fiber

A HCMF consists of the inner air core surrounding the high index outer ring core and two silica cladding as shown in Fig. 1. The numerical analysis of HCMF should be done by a full vectorial calculation rather than a weakly guiding assumption because of the large refractive index difference between inner air core and

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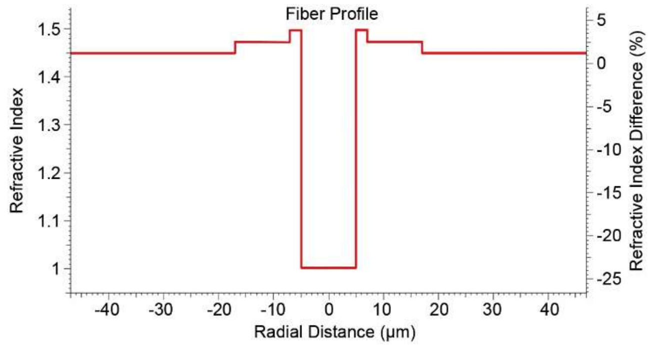


Fig. 1 — Refractive index profile of a hollow core multi clad fiber.

outer ring core. Still, mode cut-off was apprehensive, the linearly polarized, the weakly guiding approximation is still valid.

The refractive indices of the inner air core, outer ring core and cladding sections are $n_{\mathrm{air}}$ =1, $n_{\mathrm{core}}$ and $n_{\mathrm{clad}}$ = 1.49 and 1.45, respectively, and the air core, ring core and cladding radii are $r_{\mathrm{air}}$, $r_{\mathrm{ringcore}}$ and $r_{\mathrm{clad}}$, respectively. *e*(*r*) is an Eigen solution of the Helmholtz equation, which means the radial dependence of the electric field component. It can be written as follows[16]:

$$e(r) = \begin{cases} AI_l(vr)\; r < r_{\mathrm{air}} \\ BJ_l(ur) + CY_l(ur)\; r_{\mathrm{air}} \leq r \leq r_{\mathrm{core}} \\ DK_l(wr)\; r > r_{\mathrm{core}} \end{cases} \quad \ldots (1)$$

Here, *r* is the radial position, and *A*, *B*, *C* and *D* are constants. $I_l(K_l)$ is the $l^{\mathrm{th}}$ order modified Bessel function of the first (second) kind and $J_l(Y_l)$ is the $l^{\mathrm{th}}$ order Bessel function of the first (second) kind. *v*, *u* and *w* are the model parameters and they are defined as:

$$v = \sqrt{\beta^2 - n_{\mathrm{air}}^2 k_0^2} \quad \ldots (2)$$

$$u = \sqrt{n_{\mathrm{core}}^2 k_0^2 - \beta^2} \quad \ldots (3)$$

$$w = \sqrt{\beta^2 - n_{\mathrm{clad}}^2 k_0^2} \quad \ldots (4)$$

Here, the Eigen value of $k_0$ is the wave number and β is the propagation constant of every mode. By applying the continuity of electric field at two boundaries $r = r_{\mathrm{air}}$ and $r_{\mathrm{ringcore}}$, the following 4×4 matrix type characteristic equation can be obtained[17]:

$$\begin{vmatrix} I_l(vr_{\mathrm{air}}) & -J_l(ur_{\mathrm{air}}) & -Y_l(ur_{\mathrm{air}}) & 0 \\ vI_l'(vr_{\mathrm{air}}) & -uJ_l'(ur_{\mathrm{air}}) & -uY_l'(ur_{\mathrm{air}}) & 0 \\ 0 & J_l(ur_{\mathrm{core}}) & -Y_l(ur_{\mathrm{core}}) & -K_l(wr_{\mathrm{core}}) \\ 0 & uJ_l'(ur_{\mathrm{core}}) & -uY_l'(ur_{\mathrm{core}}) & -wK_l'(wr_{\mathrm{core}}) \end{vmatrix} = 0 \quad \ldots (5)$$

The propagation constant (β) can be obtained from Eq. (5) numerically and the characteristic equation has multiple solutions discrete propagation constants $\beta_{lm}$ ($m$ =1, 2…), which represents a guided mode, for each azimuthal index *l*. The transverse field distribution of each mode can be computed from Eq. (1) after determining the constants *A, B, C* and *D* from the achieved propagation constant (β) value. Primarily targets the HCMF as a distributed fiber waveguide filter for high power fiber laser operating at short wavelengths. Therefore, calculating fiber parameters for fundamental cut-off mode are the main objectives. Sequentially to achieve the fundamental cut-off mode wavelength, the propagation constant of the $LP_{01}$ mode at several core thicknesses was calculated depending on wavelength and then it was converted to the effective index, which is defined as $n_{\mathrm{eff}} = \beta/k_0$. The variant of the effective indices of the $LP_{01}$ mode depends on core thickness and wavelength at a fixed ($NA_{\mathrm{co}}$ = 0.091, $NA_{\mathrm{co}} = \sqrt{n_{\mathrm{co}}^2 - n_{\mathrm{clad}}^2}$) and hole diameter of 4 µm. Here, the refractive index of silica at 1.0 µm was 1.4571. In general, the modal cut-off conditions takes place when the effective refractive index of the guided mode becomes equal to the silica cladding refractive index.

## 3 Results and Discussion

The key features of the HCMF have been summarized for WDM optical communication systems, which was introduced the types of dispersion. Hence, it can be said 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 together are called the chromatic dispersion (total dispersion).

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

$D_{\mathrm{mat}}$ depends upon the material taken for the construction of the optical fiber. $D_{\mathrm{wg}}$ is the parameter that depends up on the structure of the fiber. According to the definitions of chromatic dispersion coefficient[18] *D*, the expressions of chromatic dispersion coefficient *D* and its slope *S* can be obtained as follows:

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

$$S = -\frac{\lambda}{C}\frac{d^2}{d\lambda^3}\left[1 + \Delta\frac{dBV}{dV}\right] - \frac{1}{c}\frac{d^2 n_4}{d\lambda^2}\left[1 + \Delta\frac{dBV}{dV}\right] + \frac{N_4}{c}\frac{\Delta}{\lambda^2}V^2\frac{d^3(BV)}{dV^3} + 2\frac{N_4}{c}\frac{\Delta}{\lambda^2}V\frac{d^3(BV)}{dV^2} \quad \ldots (7)$$

where $N_4 = n_4 - \lambda dn_4/d\lambda$ is the group index of the outer cladding and $d^{\mathrm{m}}n_4/d\lambda^{\mathrm{m}}$ ($m$=1,2,3) can be calculated by Sellmeier formula[19].

## 4 Design of Zero Dispersion Hollow Core Multi Clad Fiber

We have focused on exploiting the flexibility of the HCMF structure to create a fiber that can compensate the dispersion accumulated in transmission fibers. A more attractive way of addressing the problem of dispersion other than the addition of dispersion compensating devices to transmission systems would be to eliminate the dispersion in the transmission fibers themselves. This strategy has been widely employed using the zero dispersion shifted fibers. These are single mode silica based transmission fibers whose index profile has been tailored such that the waveguide dispersion and material dispersion balance each other's exactly. However using such fibers in DWDM systems was problematic, because zero dispersion enhances interchannel nonlinear effects such as four wave mixing. Therefore, to avoid the nonlinear effects in silica fibers, modern transmission systems employ fibers with a small, positive dispersion parameter, which necessitates dispersion compensation. The HCMF fiber structure offers a different and far more interesting solution to the problem: the HCMF transmission fibers have nonlinearities that are four orders of magnitude lower than those of silica fiber, and therefore operating the fiber at or near zero dispersion is feasible, even for multichannel systems with low channel spacing. Unfortunately, the HCMF long haul fiber does have a positive dispersion parameter on the order of 7-10 ps/km.nm, as Fig. 2 shows. It would therefore be beneficial to modify the design of this fiber to achieve zero dispersion. We do this by changing the thickness of a few of the innermost cladding so as to allow some power to penetrate into the cladding, like in the dispersion compensating fiber.

The resulting structure is equal to the structure of the long haul fiber; however, we choose to operate this fiber at the wavelength of zero dispersion. At this wavelength, less than 0.1% of the power penetrates into the cladding, and therefore the losses and nonlinearities of the cladding materials remain strongly suppressed. Absorption losses will only be an order of magnitude larger than for the long haul fiber, and because the nonlinearities of the fiber are still governed by the nonlinear coefficient of the air core, the nonlinearity of this fiber will only increase by a few percent. For power levels used in modern communication systems, we therefore do not expect nonlinear effects to play any significant role.

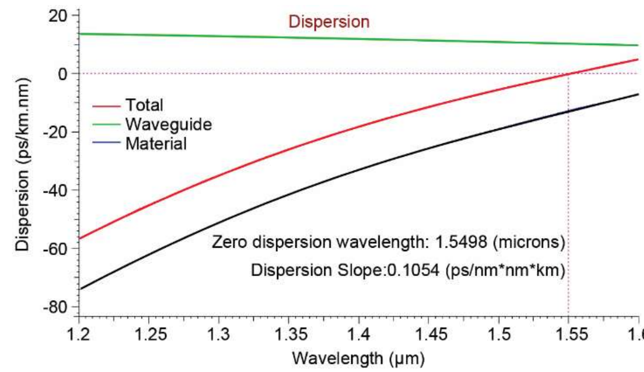


Fig. 2 — Dispersion of HCMF over a broad wavelength range.

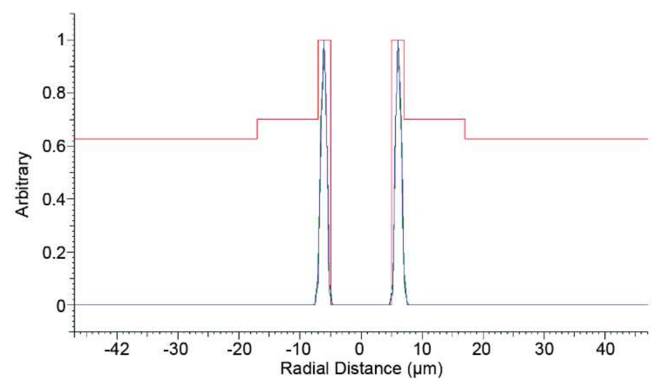


Fig. 3 — Variation of power confinement with the radial distance.

In Fig. 3, the normalized power confinement distributions along radial distance were calculated at several core thicknesses. The wavelength of the light approaches the fundamental mode cut-off of the fiber, the modal confinement factor is significantly reduced and the field gets broader. Beyond the fundamental mode cut-off where $n_{\mathrm{eff}} = n_{\mathrm{clad}}$, the modal field does not exist in the ring-core any more. This makes the HCMF suitable for a distributed wavelength filter.

## 5 Conclusions

In this paper analysis of hollow core multi-clad optical fibers, with emphasis on triple-clad structures, was presented. A novel designed HCMF is proposed to obtain dispersion based on the core and cladding radius. Unified general formulations were developed to study various transmission properties of single-mode weakly guiding cylindrical optical waveguides with hollow core and three claddings, with step-index profiles. Specific designs to achieve dispersion-shifting were proposed and analyzed. In particular, an optimum design for dispersion-shifted fibers was addressed. This fiber has a depressed core index and the first inner cladding assumes the largest index. Also, a dispersion-shifted fiber was optimized to provide zero second-order and third-order dispersions at $\lambda = 1.55\ \mu m$. Hence, a much smaller pulse spreading occurs compared to conventional dispersion-shifted fibers for transmission over long distances. This kind of HCMFs has the potential to control the dispersion more easily by changing the refractive index and width of core and cladding. The doped materials concentration changes the refractive index of core and cladding in the high and low index inclusions. The proposed fiber may be used in WDM optical communication systems.

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