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STUDY OF MODE FIELD DIAMETER IN ELLIPTICAL DEPRESSED INNER CORE TRIPLE-CLAD SINGLE-MODE OPTICAL FIBER

[1]SEYED MEYSAM ARABZADEH, [2]SOMAYEH MAKOUEI*

[1] Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran

[2] Department of Electrical and Computer Engineering, University of Tabriz, Tabriz 51664, Iran

E-mail: [1]m_arabzadeh@iau-ahar.ac.ir , [2]makouei@tabrizu.ac.ir*

ABSTRACT

In this paper, the mode field diameter (MFD) of the R-type elliptical depressed inner core triple clad single-mode optical fiber is examined. The effect of optical and geometrical parameters on the mode field diameter and the effective refractive index, are studied. Modal analysis is done by using the finite element method (FEM), and the wave equation for optical fiber is solved. Elliptical core fibers can maintain the polarization of the light wave launches into the fiber. The MFD of elliptical fibers is calculated in major and minor axes. According to the simulation results, the behavior of the mode field diameter in slow axis of elliptical fiber is close to the mode field diameter of the circular fiber. In the meantime, MFD becomes larger by the wavelength increasing. Also it is more sensitive to the optical parameters changes compared to the geometrical parameters. By increasing the core radius, the MFD becomes smaller in slow and fast axes. Among the optical and geometrical parameters, the MFD is the most sensitive to changes in the Δ *and Q.*

Keywords: ***Depressed inner core, Elliptical fibers, Mode field diameter (MFD), Single-mode fibers, Finite element method (FEM)***

1. INTRODUCTION

Looking at the telecommunications industry at today and yesterday, it will be seen that there is a dramatic change from yesterday to today that much of it is due to the optical fiber technology. Sending audio signals requires high bandwidth and optical fiber supplies it. Fibers are physical structures which are designed to transmit electromagnetic energy along a specified path with minimal loss and distortion [1-7]. Triple clad single-mode fibers due to having excellent propagation properties have attracted more attention in recent years. A triple clad fiber has been studied first by Kouzes and Boukouvalas as an optical coupler [8, 9]. In most research reports presented by the researchers, the design of optical fibers for long-haul transmission was performed by structures that have circular cross-section. Three major factors which lead to restrictions on the transfer of data through optical fibers are the loss, dispersion and nonlinear effects [1, 2, 10]. The first non-circular elliptical fibers analysis was done in 1962 by Yeh [11], he presented a precise method for calculating the propagation characteristics of elliptical waveguides, with any degree of ellipticity, using a series of Mathieu functions [12]. Years later, they used finite element techniques to obtain the propagation characteristics for waveguides with different cross-section such as triangular, rectangular, elliptical, etc. [11, 13].

Optical fibers always exhibit a degree of birefringence, even when they have a circular cross-section, because in practically, there are always some mechanical stresses or other factors affects the symmetry of the cross section. As a result, the polarization of light which is propagated in fiber gradually changes, depends on any bend in the fiber length and its temperature. The mentioned problem can be fixed by using a polarization-maintaining fiber, which is not a fiber without birefringence, but on the contrary a specialty fiber with a strong built-in birefringence (high-birefringence fiber or HIBI fiber, PM fiber) [14]. Dyott showed that an elliptical double-clad step index fiber can maintain polarization, if the difference between the indices of refraction of the layers is large. He also stated that an elliptical triple-clad step index fiber must have a larger core to maintain polarization [15, 16]. If the polarization of light launched into the fiber is aligned with one of the birefringent axes, this polarization state will be preserved even if the fiber is bent. The physical principle behind this can be understood in terms of coherent mode coupling. The propagation constants of the two polarization modes are different due to the strong birefringence. Fibers with an elliptical core can maintain the polarization of the light wave launches into the fiber. Birefringence of the elliptical fibers can be increased by increasing ellipticity of the core. Zero polarization mode dispersion and high birefringence can be obtained by an elliptical depressed inner core single-mode fiber [17-19].

Propagation characteristics of optical fibers with an elliptical cross-section have been studied by many researchers, but a special types of optical fibers are known according to the refractive index profile as the R, W and M type [5, 7-9, 20] give some desirable properties and unique characteristics not found in standard optical fibers [11, 21]. In this paper, the mode field diameter (MFD) of the R-type elliptical depressed inner core triple clad single-mode optical fiber is studied. For the analysis, the finite element method will be used. This fiber has a structure that its dispersion curve is flattened. Since, this structure has large cross-section, non-linear effects will be very low, and this structure can be used for long haul transmissions. For having OTDM and DWDM system with high capacity and speed, an optical fiber with small dispersion as well as the small dispersion slope and uniform dispersion curve in the practical wavelength duration will be required. One of the major potential of R-type, having a large effective area causes to prevent the nonlinear effects, such as four-waves mixing which occurs in long haul transmissions, and will appear because of the Non-implementation of phase.

This paper is organized as follows:

Mathematical formulation and modal analysis are presented in the Section 2. In this section, mode filed diameter relation and optical and geometrical parameters will be reviewed, as well as the finite element method will be mentioned. Simulation results and discussion are presented in section 3. Finally, the paper ends with conclusion.

2. MATHEMATICAL FORMULATION

In this section, the mathematical equations of the MFD and optical and geometrical parameters will be presented and the fiber structure completely will be introduced. The structure of the R-type elliptical depressed inner core triple clad single-mode optical fiber is one of the structures with the depressed inner core. Figure 1, shows the refractive index profile of the layers, which are defined as below:

$$n(r) = \begin{cases} n_1, & 0 < r < a \\ n_2, & a < r < b \\ n_3, & b < r < c \\ n_4, & c < r \end{cases} \quad (1)$$

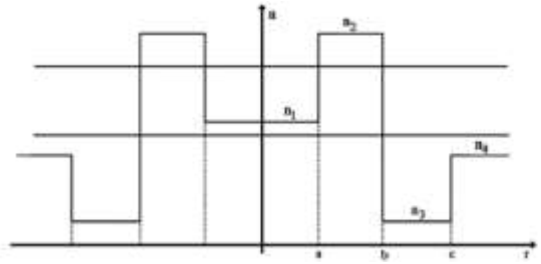

Figure 1. The refractive index profile of the R-type fiber.

Where, r is Position Vector of the radius of the fiber.

Optical parameters are defined as follows:

$$\Delta = \frac{n_2^2 - n_4^2}{2n_4^2} \approx \frac{n_2 - n_4}{n_4}, \; R_2 = \frac{n_1 - n_4}{n_2 - n_1}, \; R_1 = \frac{n_2 - n_3}{n_2 - n_1} \quad (2)$$

And geometrical parameters also are considered as the follows:

$$Q = \frac{a}{c}, \; P = \frac{b}{c}, \; L = \frac{a}{a'} = \frac{b}{b'} = \frac{c}{c'} \quad (3)$$

Where a', b' and c', respectively are the minor radius of the core and claddings, and geometrical parameter, L, shows the ellipticity of fiber cross-section, that in this paper the value of L is considered equal to 2.

The MFD is defined as follows:

$$d_0^2 = 8 \frac{\int_0^\infty |\psi(r)|^2 r dr}{\int_0^\infty \left|\frac{d\psi(r)}{dr}\right|^2 r dr} \quad (4)$$

A perfect dielectric environment is an environment where σ = 0. Because for making optical devices, such as optical fiber, glass is used, so σ = 0. Therefore, Maxwell's equations would be simplified as follows:

$$\nabla^2 \vec{E} = \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} \quad (5)$$

$$\nabla^2 \vec{H} = \mu\varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} \quad (6)$$

For an environment with electrical permittivity ε_r, the wave equation for the electric field will be as follows:

$$\nabla^2 \vec{E} + \nabla\left(\frac{\nabla\varepsilon_r}{\varepsilon_r} \cdot \vec{E}\right) + k_0^2 \varepsilon_r \vec{E} = 0 \quad (7)$$

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Where k_0 is the wave number in vacuum and is expressed as below:

$$k_0 = \omega\sqrt{\varepsilon_0\mu_0} \tag{8}$$

When the electrical permittivity ε_r is constant in the environment, wave equation is reduced to the Helmholtz equation:

$$\nabla^2\vec{E} + k_0^2\varepsilon_r\vec{E} = 0 \tag{9}$$

According to the refractive index equation in the dielectric, the wave equation for the electric field is rewritten as follows:

$$\nabla^2\vec{E} + k^2\vec{E} = 0 \tag{10}$$

In this paper, modal analysis is done by using the finite element method (FEM), and the wave equation for optical fiber is solved. In mathematics, the finite element method is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It uses subdivision of a whole problem domain into simpler parts, called finite elements, and variational methods from the calculus of variations to solve the problem by minimizing an associated error function. Analogous to the idea that connecting many tiny straight lines can approximate a larger circle, FEM encompasses methods for connecting many simple element equations over many small subdomains, named finite elements, to approximate a more complex equation over a larger domain. In the execution of the finite element method, the cross-section Ω of the optical waveguide concerned is first suitably divided into a number of sub domains or elements. Various types of elements are available for the finite element techniques. Elements are classified as one-, two-, and three-dimensional. The simplest example in one dimension would be a piecewise continuous linear function or, but for a more elaborate element it can be piecewise quadratic function. In two dimensions the elements are often triangles or rectangles. The simplest triangular element assumes a linear interpolation between the field values at the corner points (vertices) of the triangle. Within each of these elements the trial function is approximated by a suitably chosen polynomial. In the simplest case the elements are triangular and first degree polynomials are used. By this procedure the transverse plane is covered with a grid of discrete nodes, which coincide with the corners of the triangles [22]. Finally, the wave equation is solved by using finite element method for different wavelengths for desired fiber by applying boundary conditions, and propagation mode has been achieved. In the following figure, meshing of the fiber cross-section is shown.

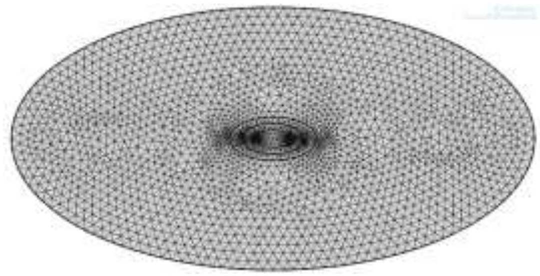

Figure 2. Meshing of the fiber cross-section.

3. SIMULATION RESULTS AND DISCUSSION

In this section, the effects of variation of the optical and geometrical parameters on the effective refractive index and the MFD curves are examined. In order to investigate the effects of these parameters on the MFD and effective refractive index curves, each parameter is varied one at a time while the others are kept constant. These simulations have been done according to a=2.6 µm, Q = 0.4, Δ = 3.35e-3, P = 0.76, R_1 = 3 and R_2 = 0.5. Geometrical parameter L, in all simulations is considered 2, and the desired wavelength duration is considered between 1.3 to 1.65 µm. The effect of changes in the optical and geometrical parameters on the effective refractive index curves is shown in the following figures. According to these figures, it is seen that, by increasing the wavelength, the effective refractive index decreases, which it is exactly consistent with the behavior of circular fiber [20]. In each simulation effect of single parameter is studied and others are kept constant. A brief glances on the presented figures in this part exhibit that the MFD becomes larger by the wavelength increasing. In the case of elliptical fibers, for the MFD, two numbers are reported, the major and minor axes are corresponding to slow and fast axes, so MFD are calculated in slow and fast axes.

Figure 3, shows the effect of the core radius "*a*" on the n_{eff}. By increasing the core radius, the n_{eff} raises and the increment rate at short wavelengths is more. Since, by increasing the core radius "*a*", the most part of the light beam is confined in the core and the first cladding layer and in the second and third cladding layers light beam is damped, so the rate of decline of the electrical field raises, therefore the MFD becomes smaller in both axes, however the case is a little complicated at the short wavelengths. The electrical field is localized in the core region of the fiber at the short wavelengths innately. Thus the

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MFD is insensitive to the core radius "*a*" at the short wavelengths almost. Figure 4 shows the core radius "*a*" effect on the MFD. It is observed that the MFD is reduced in both slow and fast axes by the core radius increasing. The reduction rate in both axes is more for longer wavelengths. According to the Figure 4 it can be found out that the core radius has inappreciable effect on the MFD in both axes at the short wavelengths.

The *P* influence on the n_{eff} is shown in Figure 5. According to this figure, by increasing the *P* the n_{eff} raises and the rate of the increment is a little more at the short wavelengths.

In fact, by increasing the *P*, the distribution of the electrical field in the core region is smoother, and the rate of the field reduction raises at the outer layers of claddings. It can be said that the field will be led to be more compact by increasing the n_{eff}, this event makes the MFD to reduce. Figure 6 illustrates that by increasing the *P*, the MFD reduces, which the rate of reduction is larger at the longer wavelengths in slow and fast axes.

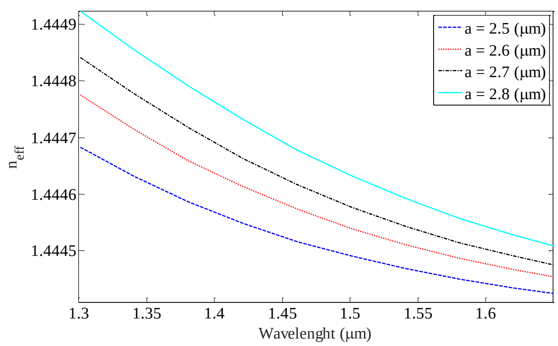

Figure 3. n_{eff} vs. wavelength (µm) for the core radius as a parameter.

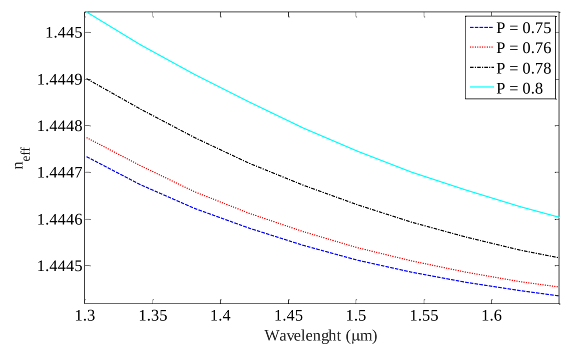

Figure 5. n_{eff} vs. wavelength (µm) for the P as a parameter.

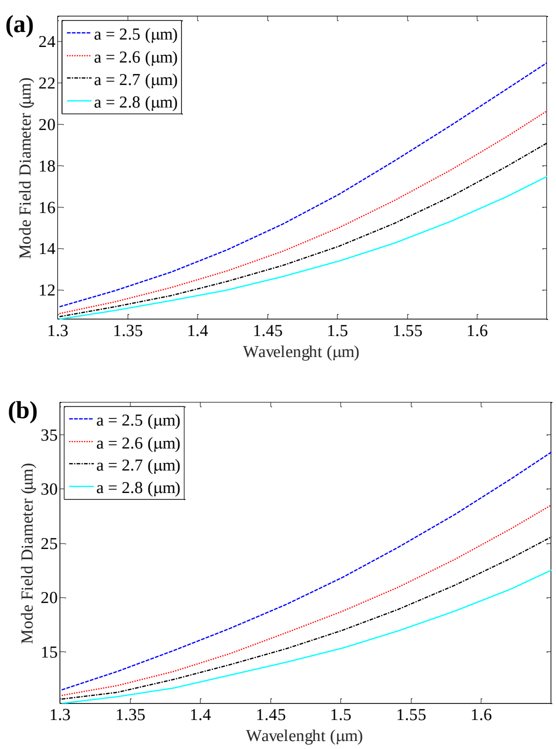

Figure 4. MFD (µm) vs. wavelength (µm) for the core radius as a parameter: (a) slow axis and (b) fast axis.

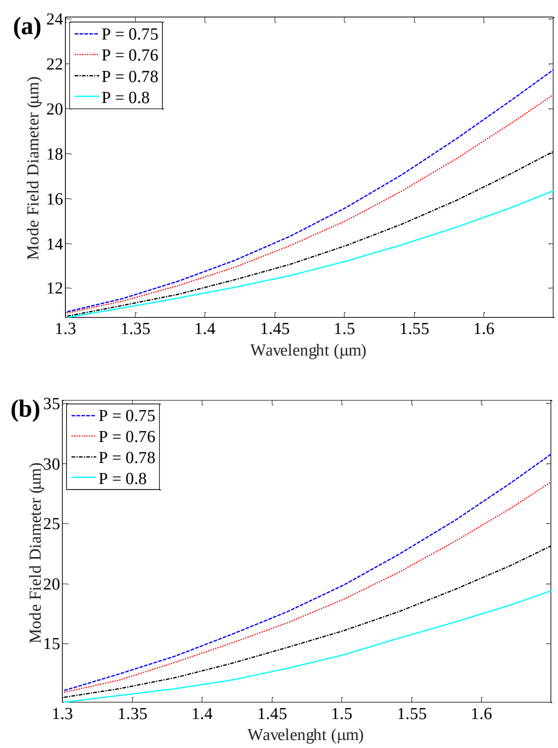

Figure 6. MFD (µm) vs. wavelength (µm) for the P as a parameter: (a) slow axis and (b) fast axis.

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Figures 7 and 8 illustrate the effect of the Q, respectively, on the n_{eff} and the MFD curves. According to Figure 6, it can be said that the n_{eff} decreases by increasing the Q. Reduction of the n_{eff} at the short wavelengths is slightly more and causes expansion of the electrical field and more influence to the outer layers of the claddings. The Q influence on the MFD is shown in Figure 8. It is clear that by increasing the Q, the MFD boosts severely at the longer wavelengths, furthermore the MFD is more sensitive to greater values of the Q and for both slow and fast axes, the increment rate is more for the longer wavelengths, i.e., the longer wavelengths are more sensitive to variation of the Q.

Figure 9 is illustrated to demonstrate the Δ effect on the n_{eff}. It is found out that the n_{eff} increases by the Δ increasing, and variation of the Δ has a strong effect on the n_{eff}. Shorter wavelengths are more sensitive to greater values oh the Δ. Increasing of the n_{eff} causes the electrical field to be bounded in the core and first cladding layer region and attenuation occurs in the outer layers of cladding, because the Δ represents the first cladding layer refractive index (n_2) therefore makes the MFD to reduce significantly by increasing the Δ. The effect of the Δ on the MFD is shown in Figure 10. According to this figure, it is clear that the Δ has a strong influence on the MFD in both slow and fast axes which is obviously seen at longer wavelengths. According to the Figures 9 and 10, n_{eff} and the MFD are more sensitive to higher values of the Δ.

In Figures 11 and 12, the influence of the R_1 can be seen. Figure 11 shows that the n_{eff} decreases by the R_1 increasing and the rate of the reduction is the same for short and long wavelengths approximately. Figure 12 illustrates the effect the R_1 on the MFD. It is found out that in fast axis, the MFD increases by the R_1 increasing, but in slow axis the case is inverse at the shorter wavelengths, because by increasing the R_1, the refractive index of the second layer of cladding (n_3) decreases, therefore the electrical field reduction ratio increases in the first and second layers of claddings, and reduces in the outmost layer of cladding but in fast axis, by the R_1 raising, the field becomes more spread, so the MFD increases in fast axis at the shorter and longer wavelengths.

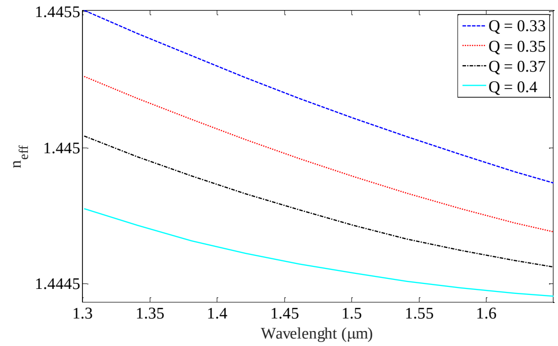

Figure 7. n_{eff} vs. wavelength (µm) for the Q as a parameter.

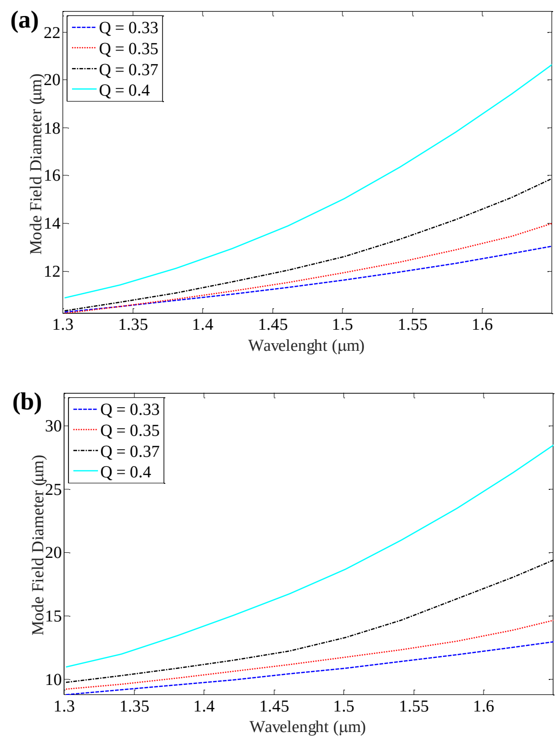

Figure 8. MFD (µm) vs. wavelength (µm) for the Q as a parameter: (a) slow axis and (b) fast axis.

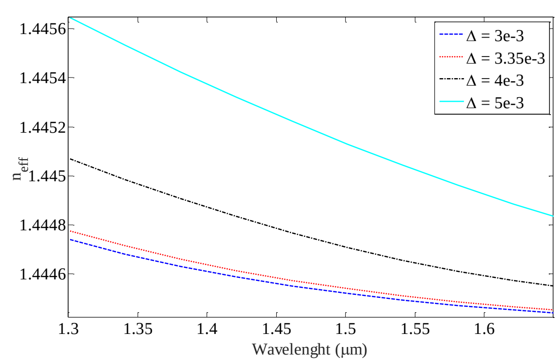

Figure 9. n_{eff} vs. wavelength (µm) for the Δ as a parameter.

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Finally, the effect of the R_2 is studied as the last parameter. Figure 13 shows that, n_{eff} increases by the R_2 increasing and the rate of increment is almost identical at the short and long wavelengths. According to Figure 14, the MFD in fast axis decreases by the R_2 increasing. With notice on this figure, it is clear that the MFD values are greater at longer wavelengths. In slow axis, at the shorter wavelengths, the MFD increases by the R_2 raising and this increment of the MFD is happened for larger values of the R_2, but the case is inversed at the long wavelengths for greater values of the R_2. In order to clarify, it can be said that the MFD decreases by the R_2 increases at the long wavelengths. Because by variation of the R_2, the core and second cladding layer refractive indices (n_1 and n_3) grow. Due to increment of the n_3, the concentration of the light beam in the core region decreases, so the MFD raises at the shorter wavelengths. However by increasing the refractive index, the field penetrates in the outer layers of cladding and causes the MFD to reduce at the long wavelengths. It is clear that smaller values of the R_2 have the remarkable effect on the MFD compared to larger values.

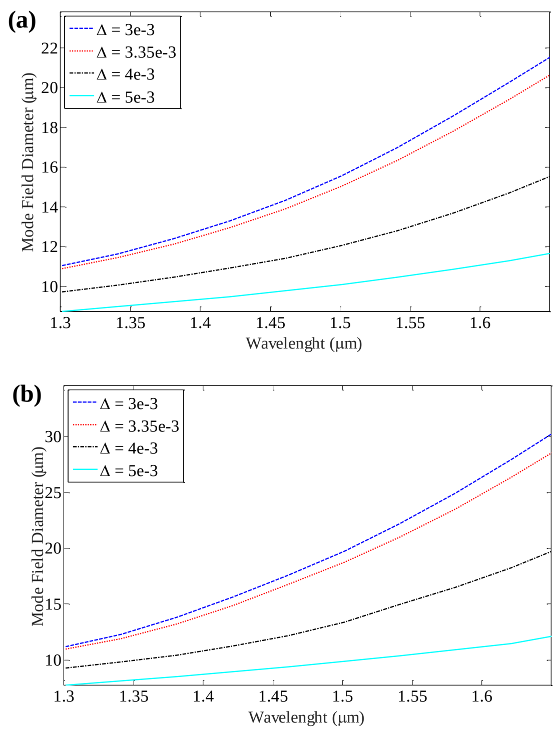

Figure 10. MFD (μm) vs. wavelength (μm) for the Δ as a parameter: (a) slow axis and (b) fast axis.

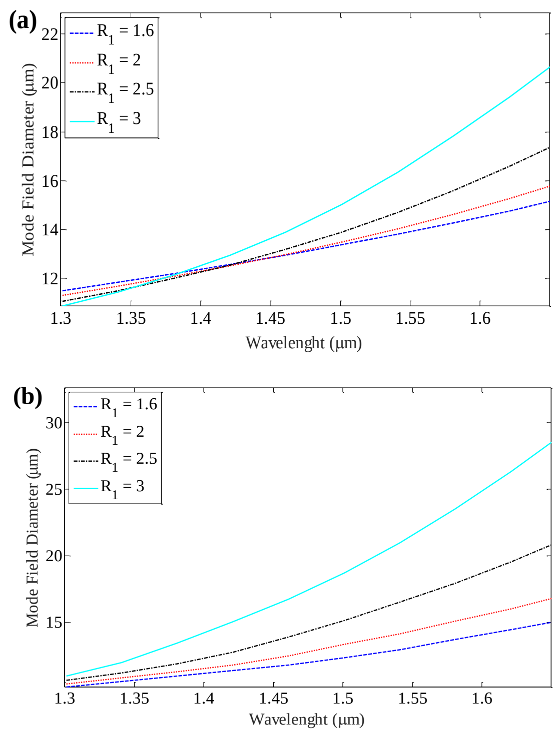

Figure 12. MFD (μm) vs. wavelength (μm) for the R_1 as a parameter: (a) slow axis and (b) fast axis.

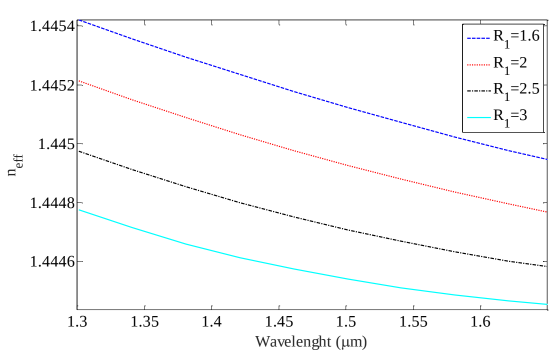

Figure 11. n_{eff} vs. wavelength (μm) for the R_1 as a parameter.

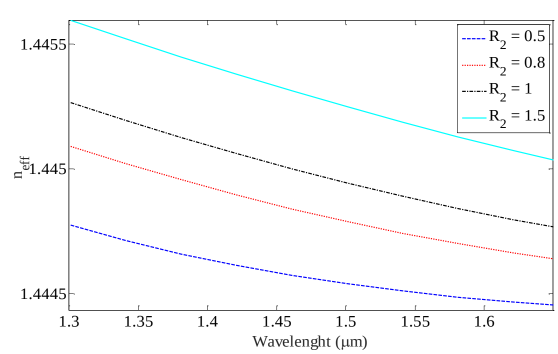

Figure 13. n_{eff} vs. wavelength (μm) for the R_2 as a parameter.

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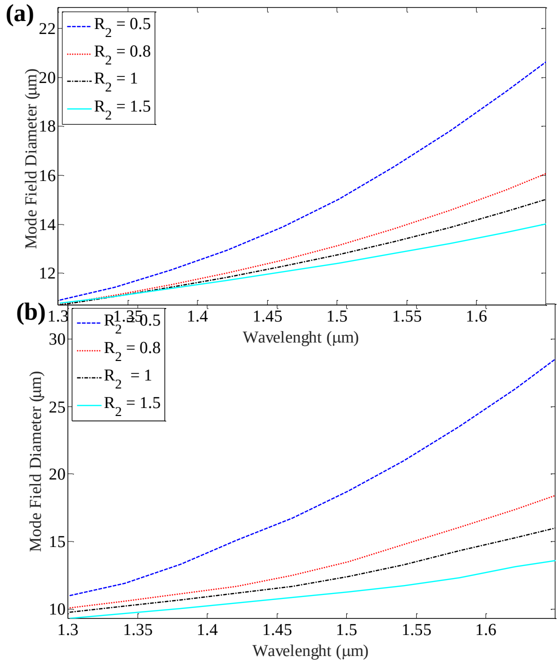

Figure 14. MFD (µm) vs. wavelength (µm) for the R_2 as a parameter: (a) slow axis and (b) fast axis.

4. CONCLUSION

In this paper, the mode field diameter of the R-type elliptical depressed inner core triple clad single-mode optical fiber is examined, and the influence of optical and geometrical parameters on the mode field diameter and effective refractive index curves were investigated. According to the simulation results, it is shown that, generally, with increase of the wavelength, the effective refractive index decreases, which is exactly consistent with the behavior of the circular R-type triple clad single mode fiber. Also, for the mode field diameter, two values, one in the main axis, and the other in the minor axis is defined, according to the results obtained from circular fibers, it is observed that the behavior of the mode field diameter in slow axis of elliptical fiber is close to the mode field diameter of the circular fiber. By the core radius increases, the mode field diameter in both the fast and slow axes is declined. Also, it found out that the mode field diameter is more sensitive to the optical parameters than geometrical parameters. Consequently among the optical parameters, the mode field diameter is the most sensitive to changes in the Δ, and among the geometrical parameters, is the most sensitive to changes in the Q as the mode filed diameter reduces significantly by increasing the Δ and with increase of the Q, raises.

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