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Design of a double clad optical fiber with particular consideration of leakage losses

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In this paper we present a double clad optical fiber that consists of core, inner cladding and outer cladding. The refractive index of the core and the outer cladding are the same and the value of refractive index of the core is greater than the refractive index of inner cladding. The cutoff number V_c is calculated and plotted with respect to the ratio of the radius of inner cladding and the radius of the core. Finally the leakage losses are calculated considering both the bending effect and the non-bending effect. And a comparison is made between the double clad optical fiber and a single clad optical fiber.

Key words: Bessel's function, cutoff value (Vc), cut off wavelength, loss co-efficient (2α).

INTRODUCTION

In the leaky waveguides, the low refractive index surrounding region has a finite thickness comparable to the penetration depth of the guided field and beyond this distance the medium has a refractive index equal to or greater than that of the guiding region. In such a case, the waves do not undergo total internal reflection and thus the reflection coefficient is less than unity. Such a phenomenon is known as frustrated total internal reflection (FTIR). Hence, in the waveguides, there are no perfectly guided modes. On the other hand, such waveguides have leaky modes that are characterized by a finite loss coefficient. The losses associated with these modes are calling the leakage loss. One of the characteristics of leakage loss is that large differential leakage loss between the fundamental and higher order modes is responsible for single mode operation required in LMA fibers (Ajeet et al., 2008, 2010).

EXPERIMENTAL DESIGN

Propagation of ray in a leaky structure

In the design of the double clad optical fiber we considered that the optical fiber consists of one core and two cladding that is, the inner and the outer cladding. The refractive index of the core and the outer cladding is the same.

Figure 1 shows the variation of refractive index with radius of the core, inner cladding and the outer cladding. n_1 is the refractive index of the core and n_3 is the refractive index of the cladding (value of both of these are the same). n_2 is the refractive index of the inner cladding. The value of n_3 is kept higher than that of n_2 to make the structure leaky. In the designed fiber, we have taken the radius of the core, x_1 = 5 µm, the radius of the inner cladding, x_2 = 30 µm, the radius of the outer cladding, x_3 = 50 µm, refractive index of the core, n_1 = 1.5, refractive index of the inner cladding, n_2 =1.4, refractive index of outer cladding, n_3 = 1.5. We have taken these values for analysis throughout this paper. Guided modes are those modes that are mainly confined to the film and hence their field should decay in the cover (Ajoy and Thyagarajan, 2011). Thus,

$$\beta^2 > k_0{}^2 n_2^2$$

In the leaky modes field is oscillatory in nature. Thus in leaky modes

$$\beta^2 < k_0{}^2 n_2^2$$

Where β is the propagation constant.

In Figure 2, the variation of electric field with fiber radius has been analyzed for each of the layer, that is, core, inner cladding and the outer cladding. Light propagates in core and inner cladding

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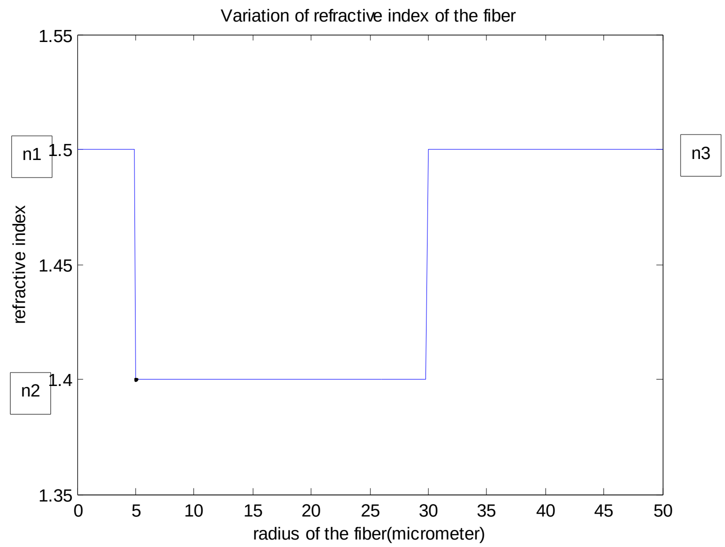

Figure 1. Variation of refractive index with the radius.

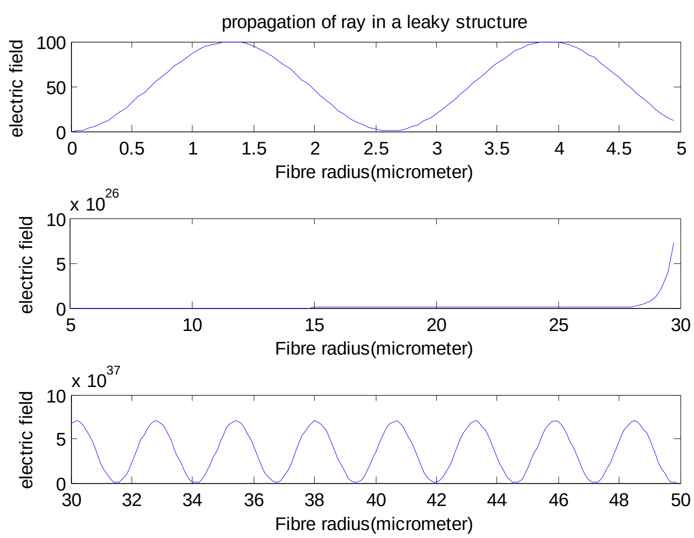

Figure 2. Variation of electric field with the radius.

in the guided mode, which implies that light will propagate in an exponential manner in these two regions. As soon as the light enters in the outer cladding, due to its leaky behavior, the light undergoes oscillatory motion. The overall propagation of the ray inside the fiber is shown in the Figure 3.

Cut-off characteristics

If β/k> n_3, then there are no leakage losses. However, if the propagation constant is smaller, so that β/k < n_3, then the mode is said to be “cut off” because power radiates through the outer cladding. Notice that if Δ = 0, as in the Figure 1, then β/k < n_3 and there are leakage losses at all wavelengths, where $\Delta = \frac{(n_1 - n_3)}{n_3}$, $\Delta' = \frac{(n_2 - n_3)}{n_3}$.

The propagation characteristics of double-clad light guides are determined from the eigenvalue equation for the weakly guiding approximation (Leonard et al., 1982; Maxim et al., 2005).

$$V_c^{\,2} = \left(2\pi \frac{x_1 n_3}{\lambda_c}\right)^2 (2\Delta) \qquad (1)$$

Where V_c is the cut off number and λ_c is the cut off wavelength. Figure 4 summarizes the cutoff behavior for the fundamental mode of the double-clad fiber. The solid curves show the cutoff value V_c as a function of the cladding radius ratio b/a for several values of the refractive index parameters H = - Δ/Δ'. A truly guided mode exists only in the region above a given curve while the area below

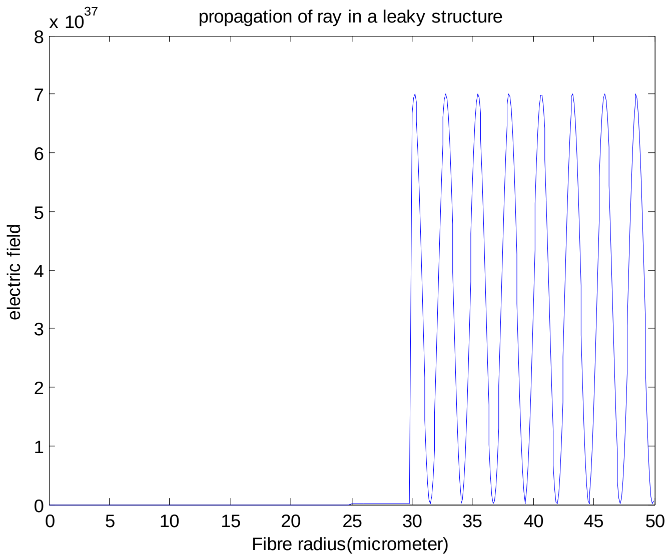

Figure 3. Overall propagation of ray inside the double clad optical fiber.

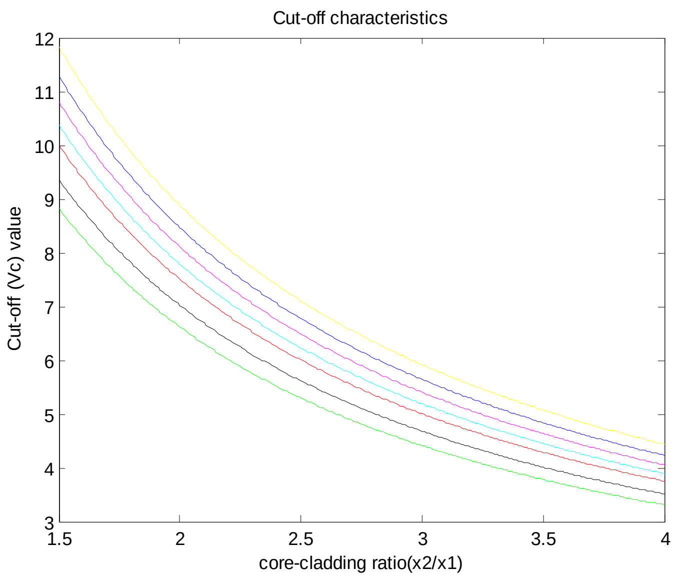

Figure 4. Graph of V_c Vs x_2/x_1 for different values of $\boldsymbol{H} = -\frac{\Delta'}{\Delta}$.

the curves indicates the region where the HE_{11} mode is cutoff because of leakage losses. No cutoff occurs if $V_c = 0$.

RESULTS AND DISCUSSION

Leakage loss calculation

The radiation losses associated with double-clad fiber with wide depressed cladding can be derived in terms of V_2, γ, σ and κ (Leonard et al., 1982).

Consider a step-index profile with either $x_2 \rightarrow \infty$ or $\Delta' = 0$. The electromagnetic field solution computed for the step-index fiber is then used as a zero-order approximation for calculating radiation losses of the double-clad fiber. This is done by introducing a reflected wave at the index step $r = x_2$ and a transmitted wave in the outer cladding at $r = x_2$. The corresponding wave amplitudes are found by requiring that the boundary conditions (Leonard et al., 1982) should be satisfied at $r = x_2$ with the zero-order field solution being regarded as an "incident" wave on the index step at $r = x_2$. The power loss coefficient 2α can be computed from the power that is radiated radially per unit length of fiber, divided by the power carried by the guided mode along the fiber axis.

Using the above procedure, the equation is derived for the power loss coefficient, 2α

$$2\alpha = \frac{2\pi\kappa^2\gamma\sigma e^{-2\gamma x_2}}{\beta n_3^2\kappa^2|\Delta'|V_2^2 K_1^2(\gamma x_1)} \quad (2)$$

Where

$$V_2 = kx_1n_3\left(2(\Delta - \Delta')\right)^{\frac{1}{2}} = [(\kappa x_1)^2 + (\gamma x_1)^2]^{\frac{1}{2}} \quad (3)$$

$$\kappa = [n_3^2(1+\Delta)^2k^2 - \beta^2]^{\frac{1}{2}} \quad (4)$$

$$\gamma = [\beta^2 - n_3^2(1+\Delta')^2k^2]^{\frac{1}{2}} \quad (5)$$

$$\sigma = (n_3^2k^2 - \beta^2)^{\frac{1}{2}} \quad (6)$$

$$\Delta = \frac{(n_1 - n_3)}{n_3} \quad (7)$$

$$\Delta' = \frac{(n_2 - n_3)}{n_3} \quad (8)$$

In Figure 5, radiative leakage losses are plotted as a function of wavelength with the cladding-to-core ratio of x_2/x_1 as the variable parameter. These losses are never zero because the HE_{11} fundamental mode is cutoff at all wavelengths. Care must be taken to choose the ratio of x_2/x_1 large enough to ensure low leakage losses within the wavelength range of interest. For example- $x_2/x_1 = 6$ is required to keep losses below 0.2 dB/km for wavelengths shorter than 1.6 µm. Throughout this paper we have assumed that the double-clad fiber has a piecewise constant refractive index distribution. Instead of solutions of the straight fiber, we use simplified WKB-type solutions (Leonard et al., 1982) of the curved structure in the derivation (2). In this way, Equation (9) for the loss of the curved double-clad fiber has been derived.

$$2\alpha(R) = \frac{4x_2\kappa^2}{\beta V_2^2 K_1^2(\gamma x_1)} \int_0^{\pi} \frac{\bar{\sigma}(x_2)\bar{\gamma}^2(x_2)e^{-2u}}{u[\bar{\gamma}^2(x_2) + \bar{\sigma}^2(x_2)]}\, d\phi \quad (9)$$

Where K_1 is the Bessel's constant

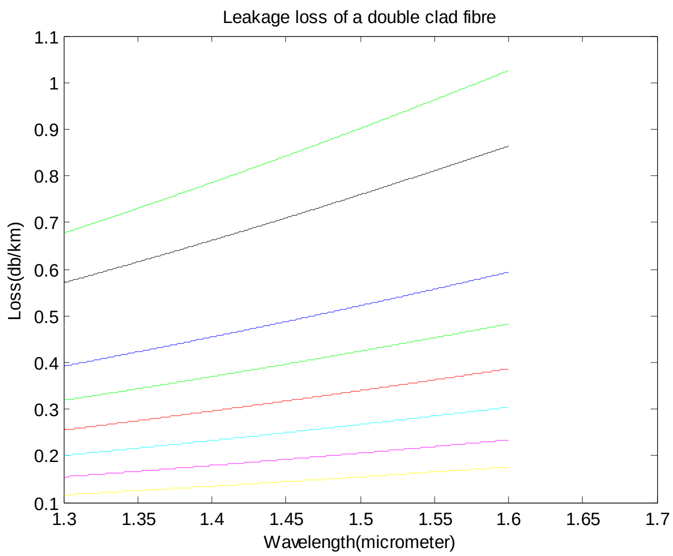

Figure 5. Variation of leakage loss Vs wavelength.

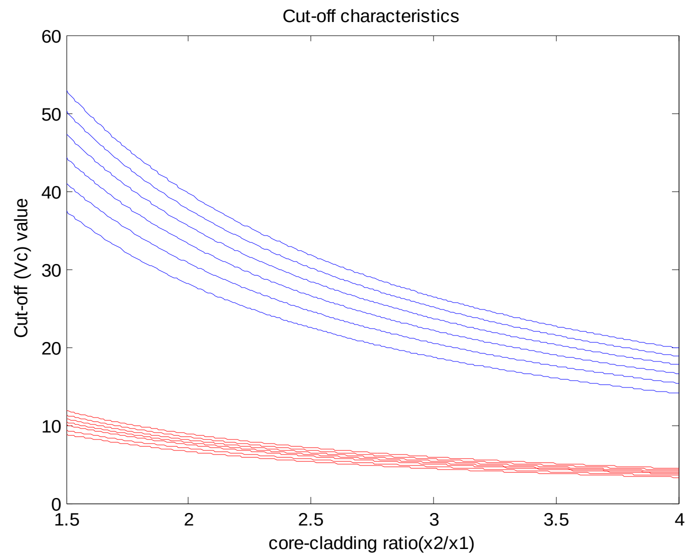

Figure 7. Comparison of cut off number Vs the core cladding ratio of the two fibers.

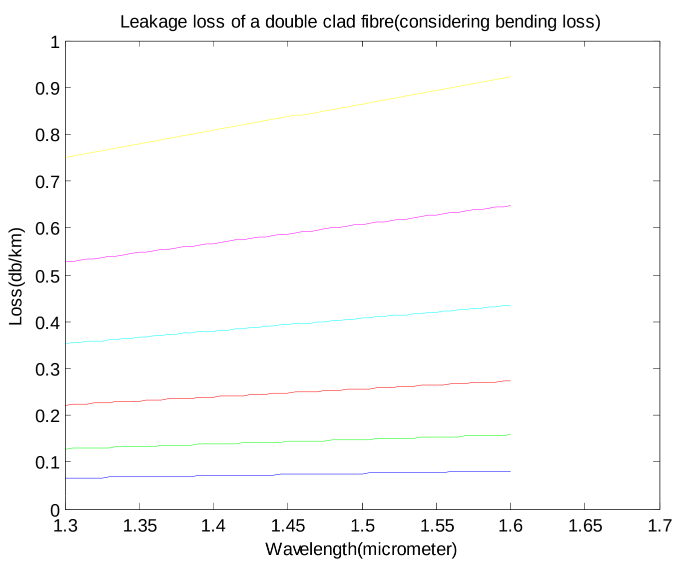

Figure 6. Variation of leakage loss considering the bending effect vs wavelength with cladding-to-core ratio x_2/x_1 as the variable parameter.

$$\bar{\gamma}^2(x_2) = \beta^2 - n_3^2(1+\Delta')^2\left(1+2\frac{x_2}{R}\cos\phi\right)k^2 \quad (10)$$

$$\bar{\sigma}^2(x_2) = n_3^2\left(1+\frac{2x_2}{R}\cos\phi\right)k^2 - \beta^2 \quad (11)$$

$$u = \frac{R[\gamma^3+\gamma^3(x_2)]}{3n_3^2(1+\Delta')^2k^2\cos\phi} \text{ for } \phi \neq \frac{\pi}{2}$$
$$= \gamma x_2 \text{ for } \phi = \frac{\pi}{2} \quad (12)$$

$$V_2 = kx_1n_3\left(2(\Delta-\Delta')\right)^{\frac{1}{2}}$$

In Figure 6, we observed that the predicted losses for a straight fiber could be significantly increased due to bending effects induced by cabling the fiber. As (x_2/x_1) increases, the bending loss also increases. For x_2/x_1 around (3 - 5) the increase in the bending loss is quite low as compared to the increase in the bending loss as the value of (x_2/x_1) goes beyond 5.

Comparisons

The design fiber with double clad has been compared with ordinary fiber at different aspects. In Figure 7, cut off number of designs fiber is denoted by the red curves and the cutoff number of the single clad fiber is denoted by blue curves. The graph is plotted by varying the value of $H = -\frac{\Delta'}{\Delta}$ for each fiber. The cutoff number (V_c) of the single clad fiber is significantly higher than that of the double clad fiber. Due to the low voice number, the double clad fiber is sensitive to bending loss and absorption loss at the cladding interface, and due to the high Vc number in single clad fiber the scattering losses in the core or at the core–cladding interface increases (Snyder and Love, 1983).

In Figure 8, the leakage losses of the designed fiber are drawn by the red lines and the leakage losses of the same fiber under bending condition are drawn with dotted lines. As clearly mentioned in the graph, for a fixed ratio of the radius of the core and cladding (x_2/x_1) the leakage losses under bending effect is more than the normal leakage losses when the value of the wavelength (λ) is (1.3 - 1.45) µm and beyond this wavelength the leakage losses are more than the bending losses. As the ratio of the radius of the core and cladding (x_2/x_1) increases, the

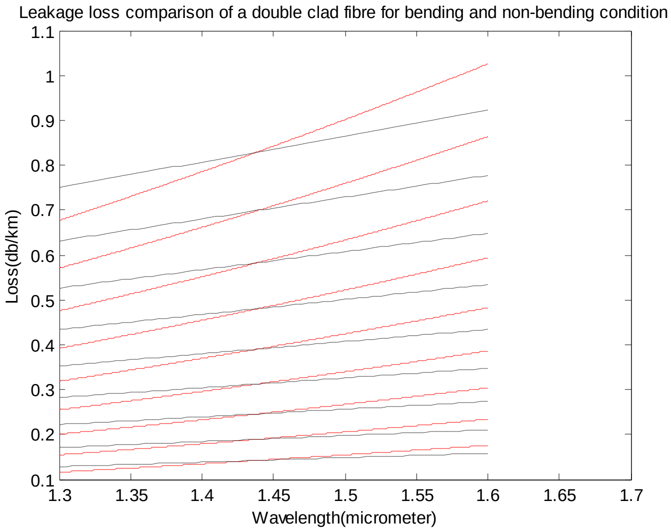

Figure 8. Comparison between the leakage losses for bending and non bending conditions in the double clad optical fiber.

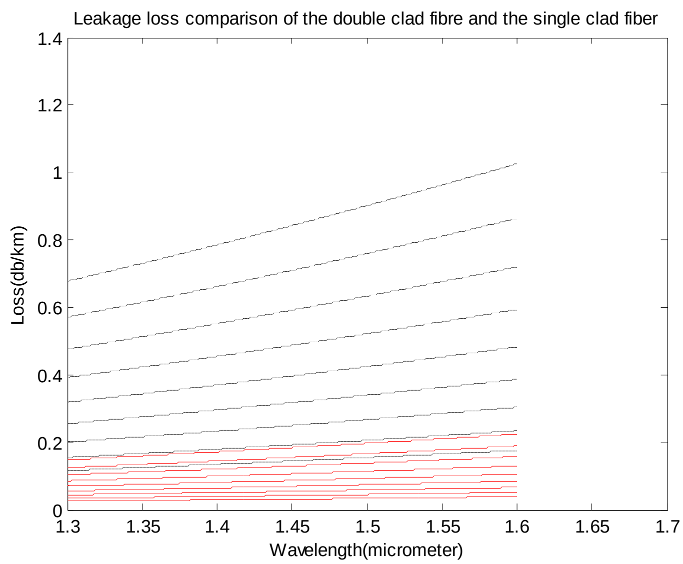

Figure 9. Comparison to the loss of leakage losses Vs the wavelength of double clad and single clad optical fiber.

slope of loss curve increases by increasing the wavelength, that is, when the ratio of x_2/x_1 is around (5 - 6), the difference in leakage loss at λ=1.3 μm and at λ=1.6 μm is quite less. But when the ratio of x_2/x_1 is around (6.5 - 9) then the difference of the leakage loss at λ=1.3 μm and at λ=1.6 μm is comparably high.

In Figure 9, comparison of the leakage losses of the designed fiber and a single clad fiber is clearly shown. The losses in the double clad fiber are drawn by the dotted lines and the leakage losses of the single clad fiber are drawn with red lines. As the ratio of (x_2/x_1) keep on increasing the leakage losses in the double clad fiber

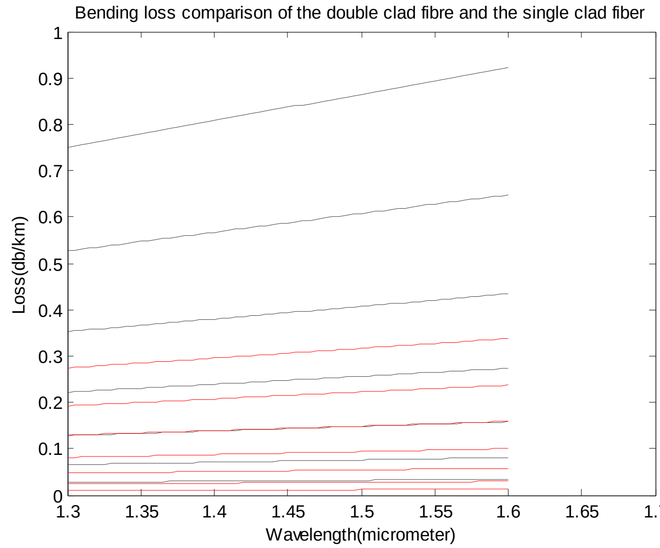

Figure 10. Comparison of the bending losses of the single clad and the double clad optical fiber Vs the wavelength.

Table 1. Table for cut-off V_c for different values of wavelength.

Wavelength (λ_c) in μm	Cut-off value (V_c)
1.2	14.33
1.25	13.76
1.3	13.23
1.35	12.74
1.4	12.29
1.45	11.86
1.5	11.47

tends to increase more as compared to the increase in the leakage losses of the single clad fiber. It occurs because of the introduction of the leaky layer in the double clad fiber, that is, the outer cladding.

In Figure 10, the bending losses of the designed fiber are drawn by the dotted lines and the bending losses of the single clad fiber are drawn with red lines. By increasing the ratio of (x_2/x_1), bending losses of double clad fiber become significantly higher than that of the single clad fiber.

Conclusion

In this paper we have proposed a design of double clad optical fiber and analyzed its characteristics at different conditions with the single clad optical fiber. It is observed that the cutoff conditions in terms of normalized curves which show the HE_{11} mode cutoff V_c number plotted as a function of x_2/x_1 by constantly varying $H = -\frac{\Delta'}{\Delta}$. From Table 1 the cut off wavelength of the double clad optical fiber is found to be 1.5 μm, since at this value of λ_c, the value of V_c is the smallest. The V_c number of the design fiber is less than the single clad fiber.

The leakage losses under the bending effect are more than the normal non bending effect for values of λ= (1.3 - 1.45) μm as shown in Figure 8. As the ratio of x_2/x_1 is around (5 - 6), the difference in leakage loss at λ=1.3 μm and at λ=1.6 μm is quite less. But when the ratio of x_2/x_1 is around (6.5 - 9) the difference of the leakage loss at λ=1.3 μm and at λ=1.6 μm is comparably high. These leakage losses and bending losses in double clad fiber increases with an increase in the ratio of x_2/x_1 as compared to the single clad fiber.

Overall we conclude that the designed fiber has less scattering loss and more sensitive to micro-bend loss as compared to the single clad fiber. The combined leakage losses and the bending losses of the double clad fiber are more than that of the single clad fiber and these losses are significantly higher when the values of x_2/x_1 are more than 5 and a value of wavelength is more than 1.45 μm.

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