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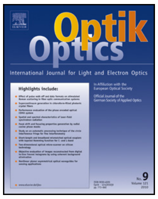

Electromagnetic analysis of novel class of multiple core/multiple clad step index single mode optical fiber by analytical means

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ABSTRACT

General propagation properties and universal curves are given for double clad single mode fibers with inner cladding index higher or lower than the outer cladding index, using the parameter: inner cladding/core radii ratio. Mode cut-off conditions are also examined for the cases. It is shown that dispersion properties largely differ from the single clad single mode fiber case, leading to large new possibilities for extension of single mode operation for large wavelength range. Paper demonstrates that how substantially we can extend the single mode operation range by using the raised inner cladding fiber. Throughout we have applied our own computations technique to find out the eigenvalue for a given modes. Detail derivations with all trivial mathematics for eigenmode equation are derived for each case. Paper also demonstrates that there is not much use of using depressed inner cladding fiber. We have also concluded that using the large inner cladding/inner core radius we can significantly increase the single mode operation range for the large wavelength region.

1. Introduction

This paper results from calculation made on double clad fiber. We observed theoretically that using double clad fiber could extend the cut-off conditions for various modes [1–4]. Theoretical results on double clad fibers with low index inner cladding and high index inner cladding have been presented [5–19]. Paper demonstrates that finding out cutoff condition for various modes can extend the single mode operation. The purpose of this paper is then to study the inner cladding effect on the propagation properties of the first guided modes of double clad fibers. This study is useful for finding out the cutoff conditions, propagation parameters, and dispersion properties for various modes. We solve numerically the Maxwell's equations for double clad fibers while providing all the mathematical details in the paper. However, as far as possible we have given the physical meaning of results, while comparing with single clad fiber [5]. Section 2 of this paper devoted to the mathematical formulation of the problem, field solutions, dispersion equation and its resolution. Section 3 deals with the results concerning the cutoff conditions for various modes. Universal curves giving the normalized propagation parameter β are shown for various cases of double clad fibers. We deduce from the data that the modal dispersion properties can be changed for fundamental mode; hence single mode operation range can be extended.

2. Modes in step index fiber

For the configuration of the step-index fiber we consider a homogeneous core of refractive index n_1 and radius a, which is surrounded by an infinite cladding of index n_2, as in Fig. 1a. The reason for assuming an infinitely thick cladding is that the guided modes in the core have exponentially decaying fields outside the core and there must have insignificant values at the outer boundary of the cladding. A mode remains guided as long as β satisfies the condition [6]

$$n_2 k_0 < \beta < n_1 k_0 \quad (1)$$

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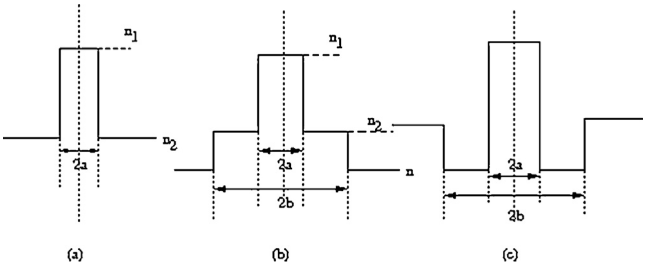

Fig. 1. (a) Step Index Optical fiber. (b) Double clad step index fiber with raised inner cladding. (c) Double clad step index fiber with depressed inner cladding.

where K_0 is the vacuum wave number. The boundary between truly guided modes and leaky modes is defined by the cut-off condition $\beta = n_2 k_0$. As soon as β becomes smaller than $n_2 k_0$, power leaks out of the core into the cladding region [7].

2.1. Modal equation

The solution for β must be determined from the boundary conditions [5]. The boundary conditions require that the tangential components of E inside and outside of the dielectric interface at $r = a$ must be the same and similarly for the tangential components H. The following eigenvalue equation is obtained after some tedious algebra [5–7].

$$\frac{\beta^2 \nu^2}{a^2}\left[\frac{1}{\gamma^2}+\frac{1}{\kappa^2}\right]=\left[\frac{J_\nu'(\kappa a)}{\kappa J_\nu(\kappa a)}+\frac{K_\nu'(\gamma a)}{\gamma K_\nu(\gamma a)}\right]\cdot\left[\frac{k_0^2 n_{\text{core}}^2 J_\nu'(\kappa a)}{\kappa J_\nu(\kappa a)}+\frac{k_0^2 n_{\text{clad}}^2 K_\nu'(\gamma a)}{\gamma K_\nu(\gamma a)}\right] \tag{2}$$

Upon solving Eq. (2) for β it will be found that only discrete values restricted to the range given by Eq. (1) will be allowed. Although Eq. (2) is a complicated transcendental equation, which is solved by discussed technique [5], its solution for any particular mode will provide all the characteristics of that mode. We shall consider this equation for some of the lowest-order modes of a step index waveguide. In Eq. (2), inside the core we define the transverse κ is given by

$$\kappa^2 = k_1^2 - \beta^2 \tag{3}$$

where $k_1 = 2\pi n_1/\lambda$, while outside the core, we define an attenuation coefficient by

$$\gamma^2 = \beta^2 - k_2^2 \tag{4}$$

with $k_2 = 2\pi n_2/\lambda$. Let us examine the cut-off conditions for fiber modes. As was mentioned in relation to Eq. (1), a mode is referred to as being cutoff when it is no longer bound to the core of the fiber, so that its field no longer decays on the outside of the core. The cutoff for the various modes is found by solving Eq. (2) in the limit $\gamma \to 0$ by using discussed techniques [5]. This is in general fairly complex, so that the results for only few modes have been given. An important parameter connected with the cut-off condition is the normalized frequency V defined by

$$V^2 = (\kappa^2 + \gamma^2)a^2 = \left(\frac{2\pi a}{\lambda}\right)^2 (n_1^2 - n_2^2) \tag{5}$$

which is a dimensionless number that determines how many modes a fiber can support. The number of modes that can exist in a waveguide, as a function of V may be conveniently represented in terms of a normalized propagation constant b defined by

$$b = \frac{a^2\gamma^2}{V^2} = \frac{(\beta/k)^2 - n_2^2}{n_1^2 - n_2^2}. \tag{6}$$

Now consider the case when $n_1 = 1.476754$, $n_2 = 1.446918$ and $a = 1.5$ μm.

Fig. 2 shows the analysis of fundamental mode HE_{11} with respect to the fiber design parameter. Fig. 2a shows that for higher wavelength range the normalized frequency is lesser than low wavelength. As we know that the fiber has less attenuation 0.2 dB/km at wavelength $\lambda = 1.55$ μm, hence corresponding the V-parameter is ≈2. Fig. 2b shows that $\kappa > \gamma$ for $V \le 2$ and $\kappa < \gamma$ for $V \ge 2$, it means that for higher wavelength region the fundamental mode will only be guided but at for lower wavelength region the power will flow through cladding region much, as it is clear from the figure that power will be linearly increases at higher value of V but the power will remains finite in the core, as κ is constant over the higher range of V number. This behavior can also see from the Fig. 2c that interpret that for higher wavelength range $\lambda \ge 3$ mode is cutoff ($\gamma \to 0$) while κ »0, hence the maximum power is total confined in the core at low frequency. Here one more point that at lower wavelength region at around 0.3 μm power is large at cladding side but some finite power may be there with core also, hence the fundamental mode will always be guided at lower frequency region. Fig. 2a and c can also be used to find out the mode cutoff condition, which is around $V = 0.6$. Plot of b (in terms of β/k_0) as a function of V is shown in Fig. 3 for few of the low-order modes.

Here we define one more design parameter is the range of guided wavelength. From Fig. 4, $\lambda \le 3$ μm, $\lambda \le 1.2$ μm, and $\lambda \le 1.22$ μm respectively are the guided wavelengths for fundamental, HE_{21} and TE_{01} & TM_{01} modes. Since we are considering here the weakly guiding approximation hence TE_{01} and TM_{01} modes are degenerate, resulting the same propagation constant. Only the HE_{11} mode will be propagated at lower frequency side.

3. Modes in double clad step index fiber having raised inner cladding

We study the structure shown in Fig. 1b. A weakly guiding fiber has a core radius a and core refractive index $n_1 \to 1.476754$. The inner cladding has a radius b and a refractive index $n_2 \to 1.461836$. The refractive index of the outer cladding is $n \to 1.446918$. This is the case