Modelling Of Optical Waveguide Using COMSOL Multiphysics

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Abstract

In this paper we investigate by simulation the dependence of the numerical aperture, normalized frequency and power propagating in the fibre, on the refractive index difference between the cladding and the core. The main purpose of the presented numerical modelling results is developing a simple method of investigating performance and optimization of single mode fibres. The numerical studies presented in this paper rely on solving the equations of electromagnetic waves propagation into optical fibres by using the finite element method technique (FEM) in COMSOL Multiphysics®.

Keywords – *single mode fibre, optical waveguide, refractive index difference, NA, COMSOL*

1. Introduction

Optical fibre systems today generate a great interest and have various applications in new communication and photonic technologies [1-5]. Advanced numerical techniques such as finite element modeling (FEM) are indispensible tools in characterisation of key fibre optic parameters [6,7]. From FEM analysis, the fibre propagation modes and dispersion characteristics can be investigated in the context of dispersion compensation and refractive index profile characterization [8-10]. In particular, the refractive index profiles of optical fibres are increasingly being designed using numerical tools.

Single mode fibres are characterised by their small core diameters. The small fibre core diameters ensure that only the fundamental mode propagates along the fibre. In single mode fibres, the refractive index difference between the core and cladding is typically very small (in the order of 0.01), so as to minimise attenuation [11]. Refractive index difference is achieved by either doping the core or doping the cladding. For glass fibres, doping with germanium or phosphorus increases the refractive index while doping with boron or fluorine decreases the refractive index [11-14]. In this paper, we demonstrate the use of FEM method in studying the behavior of single mode optical fibres using COMSOL Multiphysics® (version 4.3), a commercial software package [15].

In this study numerical mode analysis techniques were applied to single mode step index fibres. The main purpose of this numerical simulation was to obtain insights on the performance of the optical fibre with variations in refractive index of the cladding. The core diameter was fixed at 4.0 μm, which is the most commonly used diameter in literature [1-8]. The refractive index of the core was set to 1.4457 throughout the modeling study while the refractive index of the cladding was varied from 1.44030 to 1.44230 in steps of 0.0002. This range of cladding refractive indices was chosen because it maintains the numerical aperture of the fibre within 0.1, which is a common guideline used by most manufacturers [16-19]. The effect of the refractive index variation on the numerical aperture, normalized frequency and average power flow were studied for 1310 nm and 1550 nm infrared windows.

2. Theory and Numerical Modelling

In an optical fibre, light is guided by total internal reflection at the core-cladding boundary. In a step index fiber, the guidance takes place within the core as a consequence of total internal reflection at the core-cladding interface. This guiding regime is shown in Figure 1.

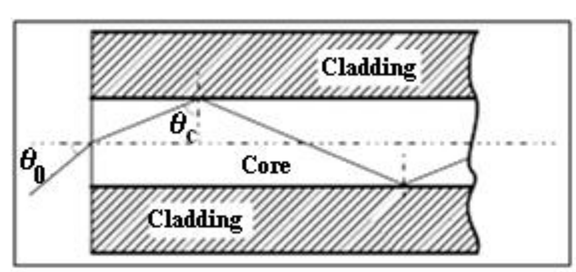


Figure 1. Light confinement through total internal reflection in step-index fibers.

More precisely, the fibre is a dielectric waveguide in which there are a discrete number of propagating modes. From Snell's law one obtains the critical angle (θ_c) for the total internal reflection at the core-cladding interface [20]:

$$\theta_c = sin^{-1}(n_{clad} / n_{core}) \qquad (1)$$

where n_{core} and n_{clad} are the indices of refraction of the core and cladding, respectively.

It can be deduced that light rays incident at the fibre end within the cone of acceptance will be trapped within the core when the cone of acceptance is defined by the maximum angle given by Eq.(2):

$$\theta_0 = sin^{-1}(n_{core}^2 - n_{clad}^2)^{1/2} \qquad (2)$$

Consequently, the numerical aperture (NA) of the step-index fibre is defined as [2,16 -18]:

$$NA = (n_{core}^2 - n_{clad}^2)^{1/2} \qquad (3)$$

NA provides an immediate indication of the characteristics of the light injection into a fibre. NA is also a measure of the light capturing ability of the fibre [19]. When describing the optical properties of a step-index fiber, the normalized frequency V is the parameter often used. It is defined as [2,21,22]:

$$V = \frac{2\pi r_{core}}{\lambda} NA \qquad (4)$$

where r_{core} is the core radius and λ is the free space wavelength. If the core diameter and the index difference, ($\Delta n = n_{core} - n_{clad}$), are sufficiently small, only a fundamental mode will propagate. The condition for single mode propagation is that the normalized frequency V be less than 2.405.

Early fibre communication systems operated at a wavelength around 0.85 µm owing to the availability of sources and detectors at this wavelength [10,11,20]. Generally, modern optical communication systems operate at wavelengths of 1310 or 1550 nm [3-5]. Figure 2 shows the infrared windows used in fibre optic systems. Operating at a wavelength of 1310 nm, in addition to being low in attenuation (about 0.32 dB/km for best fibres), it is the wavelength of minimum intramodal dispersion. Operation at 1550 nm allows even lower attenuation (minimum is about 0.16 dB/km) and the use of erbium doped fibre amplifiers, which operate at this wavelength [3-5, 20-23].

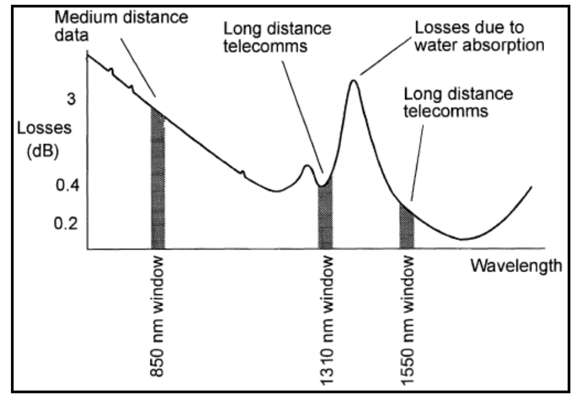


Figure 2. Attenuation versus wavelength and transmission windows for fibre optic communication [23]

The electric and magnetic fields **E** and **H** of a guided mode are solutions of source-free Maxwell's equations with **J** = 0 and σ = 0, where **J** is the current density and σ is the charge density. For time harmonic **E** and **H** fields, i.e. $\mathbf{E} = \mathbf{E_0} e^{-j\omega t}$ and $\mathbf{H} = \mathbf{H_0} e^{-j\omega t}$, then:

$$\nabla \times \mathbf{E} = j(\frac{\mu_0}{\epsilon_0})^{1/2} k\mathbf{H} \qquad (5)$$

$$\nabla \times \mathbf{H} = -j(\frac{\epsilon_0}{\mu_0})^{1/2} kn^2\mathbf{E} \qquad (6)$$

$$\nabla \cdot (n^2\mathbf{E}) = 0 \qquad (7)$$

$$\nabla \cdot \mathbf{H} = 0 \quad (8)$$

ϵ_0 is the dielectric constant of free space; μ_0 is the magnetic permeability of free space; n is the refractive index; k is the free-space wave number; $j = \sqrt{-1}$.

The solutions to Eqs. (5) – (8) were obtained using the COMSOL Multiphysics® software, which basically involves dividing the simulation domain into smaller subdomains forming a mesh. In this study, the standard meshing tool was used with the mesh setting at physics-controlled mesh and element size set to "extremely fine". A total of 25020 triangular elements with average element quality of 0.98 were used. The field equations were then discretized into an algebraic system of equations and solved for their characteristic eigenvalues. The implementation of the FEM method in COMSOL enhances an insight into the numerical methodology and analyses factors that affect its performance. As a result, computational stability, convergence rate, modelling accuracy together with the influence of time and space step lengths can all be examined.

3. Results and Discussion

The numerical aperture was found to vary linearly with the refractive index difference as shown in Figure 3. Since NA is a measure of the contrast in refractive index between the core and the cladding, it is a good measure of the light guiding properties of the fibre. The higher the NA the tighter (smaller radius) we can have bends in the fibre before loss of light becomes a problem.

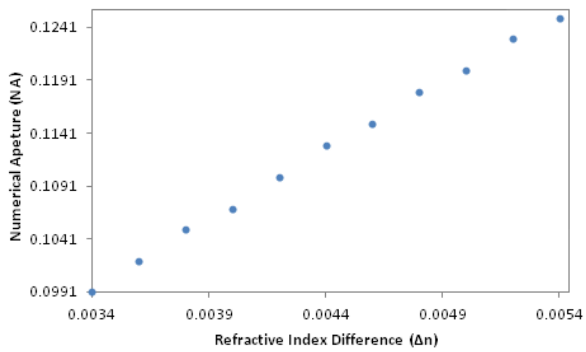


Figure 3. Numerical aperture as a function of refractive index difference.

Figures 4 and 5 show the variation of refractive index difference with normalized frequency and power respectively. For wavelengths, 1310 and 1550 nm, *V* and average power in the fibre vary linearly with change in refractive index. For the same geometrical dimensions of the fibre, operating at a wavelength of 1310 nm results in a higher values of *V* (i.e. from 1.9 to 2.4) compared to operation at 1550 nm where the values of *V* vary from 1.61 to 2.02 for variation of refractive index difference from 0.0034 to 0.0054.

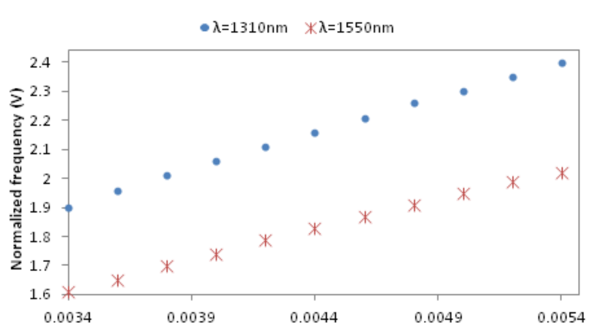


Figure 4. Variation of normalized frequency with refractive index difference.

As shown in Figure 5, operating at a wavelength of 1310 nm results in a higher power propagated along the fibre compared to operation at 1550 nm. This is also confirmed by the plots in Figures 6 and 7.

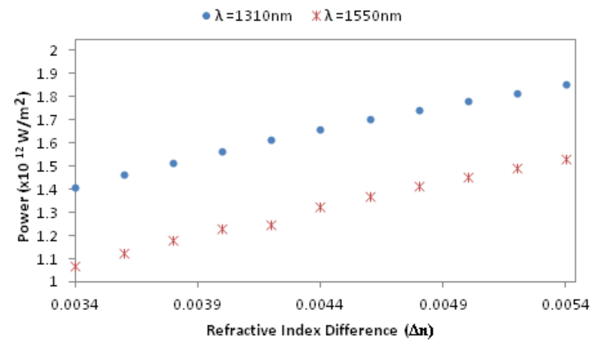


Figure 5. Variation of power with refractive index difference.

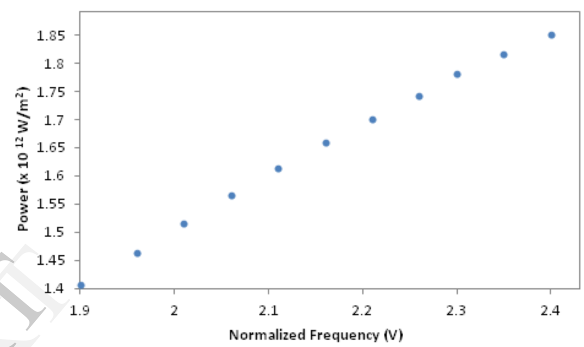


Figure 6. Variation of power with V for λ=1310 nm.

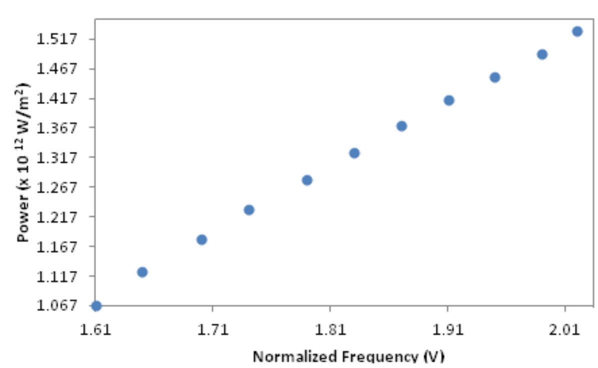


Figure 7. Variation of power with V for λ=1550 nm.

In single mode fibres, a high refractive index difference between the core and the cladding usually implies a high level of dopant in the cladding [12-14]. Since a significant proportion of optical power in single mode fibres propagates in the cladding we get a significantly increased amount of attenuation due to the higher level of dopant. Thus the higher the NA value, the higher will be the attenuation of the fibre. On the other hand, a low NA value makes coupling efficiency poor, but turns out to improve the fibre's bandwidth [22-24]. Operation close to the cutoff $V = 2.405$ risks introducing higher-order modes if the fiber parameters are not precisely targeted.

A problem with single mode fibres with low relative refractive index differences and low V values is that the electromagnetic field associated with fundamental mode (LP01) extends appreciably into the cladding [22-24]. Thus the exponentially decaying evanescent field may extend significantly into the cladding. It is therefore important that the cladding is sufficiently thick (recommended cladding diameter is 125 μm [16-19,25]), and has low absorption and scattering losses in order to reduce losses of the mode.

In single mode fibres, attenuation and speed of propagation are strongly influenced by the characteristics of the cladding material and doping levels.

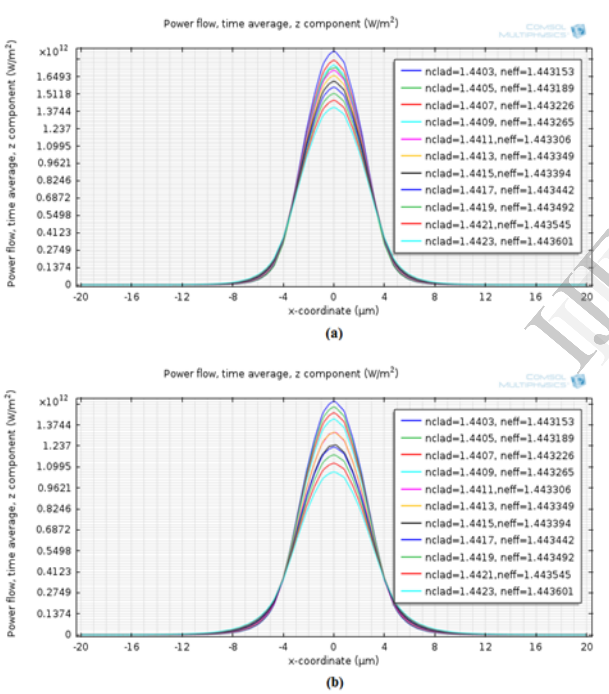


Figure 8. Variation of power flow with radial distance from fibre core centre for (a) λ=1310 nm and (b) λ=1550 nm [note: figure in colour].

Figure 8(b) shows that for λ=1550 nm, there is a sharper decrease in power flow in the fibre as the cladding refractive index increases from 1.4403 to 1.4423 compared to Figure 8(a) for λ=1310 nm. Increasing cladding refractive index increases the effective refractive index (n_{eff}) and this generally cause a reduction in the power flow along the fibre (see Figure 8)

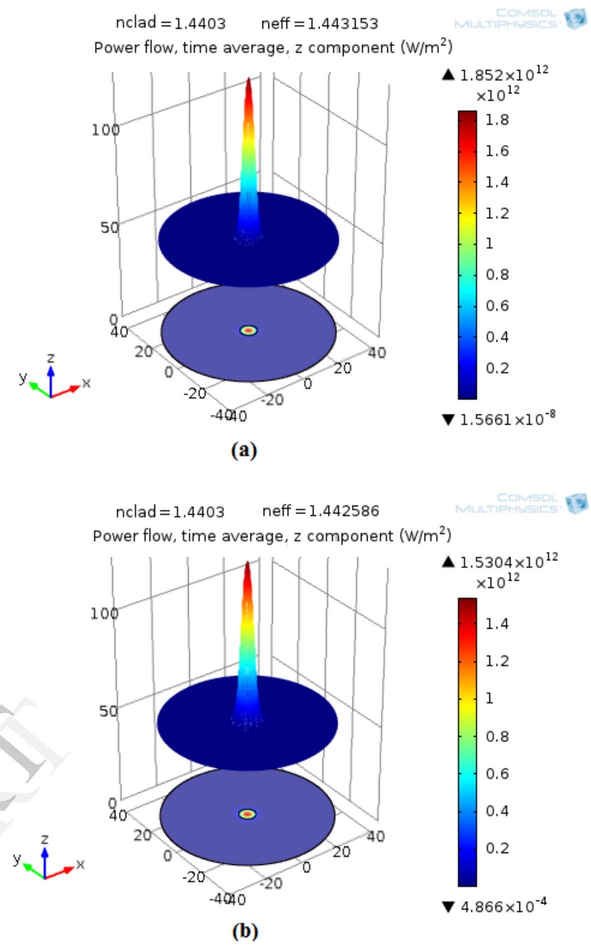
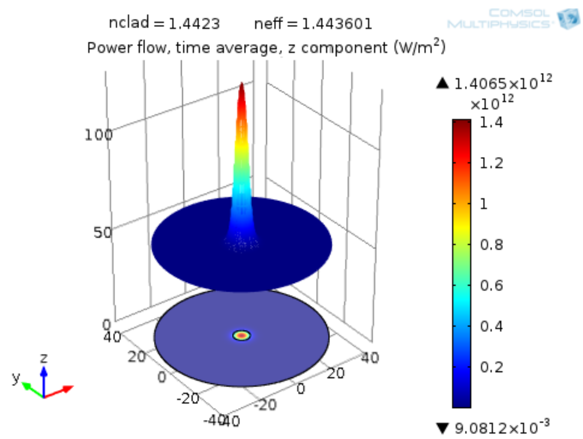
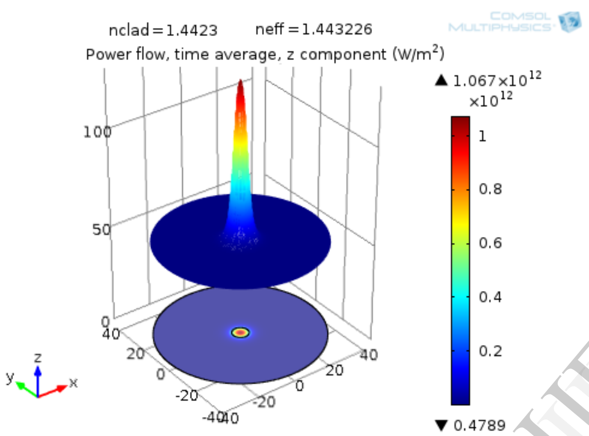


Figure 9. Variation of power flow distribution within the fibre for the fundamental (LP01) mode for operation with n_{clad} = 1.4403 at (a) λ=1310 nm and (b) λ=1550 nm

At a minimum cladding refractive index of 1.4403, operating the fibre at 1310 nm leads to higher power flow compared to operating at 1550 nm (See Figure 9). On the other hand, at maximum cladding refractive index of 1.4423, operating the fibre at 1310 nm still has higher power flow compared to operating at 1550 nm (See Figure 10). However, the order of the difference in power flow in both cases is practically insignificant and hence the fibre can be successfully operated at both 1310 and 1550 nm. This observation confirms that with the same geometrical dimensions, a single mode fibre designed to operate at 1310 nm can also operate at 1550 nm.



(a)



(b)

Figure 10. Variation of power flow distribution within the fibre for the fundamental (LP01) mode for operation with n_{clad} = 1.4423 at (a) λ=1310 nm and (b) λ=1550 nm

4. Conclusion

In this paper we have presented the results of modelling of an optical waveguide using COMSOL Multiphysics. The presented preliminary results obtained by numerical modeling represent a good starting point for improving the performance and optimization of single mode fiber optic waveguides.

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