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Effective Refractive Index and V-Parameter Characterization for Guided Modes in Multimode, Nano and Three Layer Optical Fibers

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ABSTRACT

The rapidly growing technological trends and higher data rates support has become the key feature in future communication medium selection. Multi-mode optical fiber is well matched for high data rate requirements due to its tendency to support multiple modes through one core at a time which results in higher spectral efficiency. In this research work, we have investigated the fiber design parameters Core diameter (µm), Wavelength (nm), Refractive index profile to achieve multi-mode operation and respective modal dispersion curves for each guided mode. The research work also includes the guided modes and their modal dispersion curves calculation through nano-fiber at three standard telecommunication wavelengths (850nm, 1310 nm and 1550 nm). In some special cases like tapered micro-fiber light is guided through fiber by cladding surrounding interface instead of core cladding interface. Two layers fiber architecture is not suitable for such scenarios. Guided modes have been investigated in three-layer fiber architecture to deal with such scenarios. A comprehensive analysis of Monerie, Tsao and Erdogan guided modes in three-layer fiber has also been conducted.

Keywords: *Single-mode fiber, Multi-Mode Fiber, Polarization, Linear polarization.*

1. INTRODUCTION

Fiber capacity can be increased by various methods but almost each one is limited by nonlinear mechanism due to high power requirements are involved. By proper dealing with fiber nonlinearities, capacity can be increased by significant factor [1-3]. One promising method to deal with fiber nonlinearities is by increasing core diameter which results in to multi-mode fiber [4-5]. Multi-mode optical fiber cable is well matched for high data rate throughput requirements due to its tendency to support multiple modes through one core which results in to higher spectral efficiency [4]. To achieve multi-mode operation while maintaining the nonlinear factors under the limiting range effective refractive index and V-parameter characterization is required. Guided modes through fiber core are defined by $neff$ and v-parameter values [6]. If n1 is core refractive index and n2 is clad refractive index , modes propagation through waveguide must follow the condition specified by equation 1 [6-9].

$$n2 \leq neff \leq n1 \qquad (1)$$

$$neff = n_l + n_n \qquad (2)$$

In equation 2first term denote the linear refractive index whereas 2nd term is refractive index variations due to non-linearities [8]. Sum of both terms results in to effective refractive index of any material. Modal properties of waveguides are characterized by V parameter calculation. It decides how many modes are propagating through optical fiber. V parameter is as follows [6-7]:

$$V = \frac{2\pi a}{\lambda}\sqrt{n1^2 - n2^2} \qquad (3)$$

If v-parameter value is greater than 2.405 it results in to multi-mode operation. In this research article guided modes have been investigated as linearly polarized (LP) modes. LP modes are the modes of optical fiber with assumption of weakly guidance having radically symmetric index profile. In weakly guiding assumption fiber modes calculation is very simplified because it is limited to only linear polarized modes (LP modes). In strong guidance fiber mode calculation is bit complicated because one must differentiate between TE and TM modes [6] [8-10]. Modes having Beta values between wave number of core and cladding are referred to as guided modes. If β-value is close to cladding wave-number (lower limit) then it results in to slow decay in cladding. Guided modes in a fiber can be defined by their effective refractive index profile [9-10]. Only those modes having effective refractive index between refractive index of core and cladding are referred to as guided modes in optical fiber. Effective refractive index of a fiber can be computed by dividing its beta factor by vacuum wave no [10]. The intensity profile of the lowest order mode (LP_{01}) is like Gaussian profile especially in case of small V number value. Higher value of m results in to radial component oscillation in fiber core [10-11]. These linearly polarized (LP) modes, designated as LP_{lm}, are good approximations of exact modes TE, TM, HE and EH.

The mode subscripts ‘1’ and ‘m’ are describing the electric field intensity profile of each mode as in Fig. 1. There are 2l field maxima around the fiber core circumference. And m field maxima along the fiber core radial direction [10].

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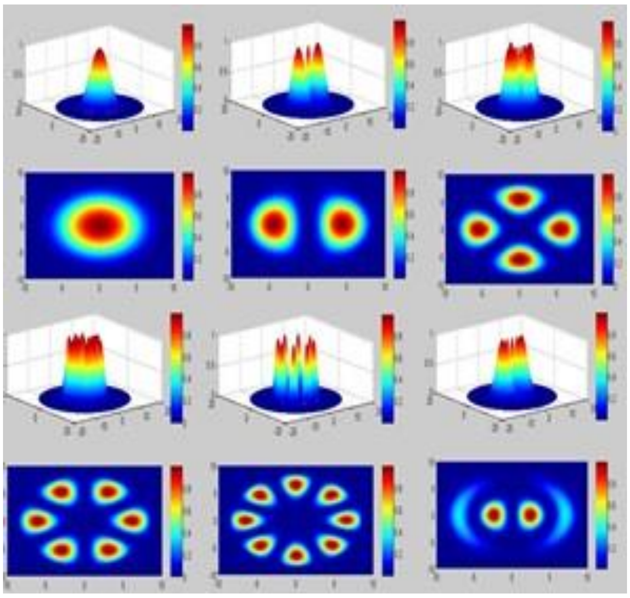

Fig. 1: Electric field amplitude profiles of LP_{01}, LP_{11}, LP_{21}, LP_{31}, LP_{41} and LP_{12}.

The basic theory for propagation of multiple modes through same fiber core at a time is Mode Coupling Theory. In this theory a wide variety of devices and systems are modeled as coupled resonators. The essence of couple mode theory is to treat the compound waveguide structures as collection of one or more simpler waveguides [7-9]. The modes of each individual waveguide are perturbed by presence of other modes associated with other waveguides and any additional non-uniformity. These perturbation results in to coupling or exchange of power among the guided modes [8-11]. Couple mode theory is reformation of Maxwell equation with the boundary conditions satisfied. Mode coupling in optical fiber can be described by two different models 1) Field coupling model 2) Power coupling model [8]. Field coupling model describe the changes in Eigen values that are the result of mode coupling. Power coupling models focuses on energy exchange between the modes and its dependence on mode fields and perturbations. It does not explain the changes in Eigen values and Eigen modes that are a result of mode coupling [8-12].

2. SIMULATIONS WORK

Nano-Fiber are the specially designed fiber having very small core diameters values usually in range of 100 nm to 1000 nm. Due to small very small core diameter they are very useful in future miniaturized technologies. In this research article simulations have been performed to achieve guided modes through such small core diameter at three standard telecommunication wavelengths. Typical communication fiber consists of 2 layers core and cladding [13]. Light is guided through fiber core by core cladding interface and does not range to the outer cladding surface. But in distinctive cases like tapered optical micro fiber light is guided through fiber by cladding surrounding interface instead of core cladding interface [2] [15]. So, three-layer fiber is designed to describe light propagation through fiber in such scenarios.

Simulation work has been performed in three steps. In first step standard two layers optical fiber cable is investigated to achieve multi-mode operation. Simultaneous propagation of five LP modes (LP_{01}, LP_{11}, LP_{21}, LP_{31}, LP_{12}) is achieved. For each mode effective refractive index value is maintained between refractive index of core and clad. Due to low losses at 1550 nm widow fiber design parameter (core diameter) has been investigated to achieve the guided modes up to this optical window. In second step simulations have been performed for nano-fiber. Guided modes investigation through very small core diameter has been performed at all three standard telecommunication wavelengths (850nm, 1310 nm, 1550 nm). Simulation results have shown that at low loss 1550 nm window only basic mode (LP_{01}) can be guided through nano-fiber. In last step guided modes through three-layer optical fiber cable have been analyzed. Comprehensive comparison of exact method guided modes with Monerie, Tsao and Erdogan guided modes is also performed.

3. RESULTS AND ANALYSIS

3.1 Simulation Results for Standard Fiber

We have used SM-800 as core and Silica with refractive index 1.544 as Clad in standard fiber case. Index step size is 0.005 which results in to weakly guidance approximation. In weak guidance the mode HE_{11} is sometimes denoted as LP_{01} mode and the HE_{21}, TM_{01}, TE_{01} mode triplet as LP_{21} mode. Simulation was performed for following fiber core diameter values 5µm, 5.6µm, 5.9µm, 6µm, 7µm, 8µm, 9µm, 10µm, 11µm, 12µm, 14µm, 16µm, 18µm.

For diameter values from 5µm-5.9 µm V-parameter is < 2.405 which is case of single mode propagation. The simulation results, as shown in Fig 3, have also verified that only one mode LP_{01} is guided through fiber core for diameter range from 5µm to 5.9 µm. For this case LP_{01} is guided mode for all three standard telecommunication wavelengths (850 nm, 1310 nm, 1550 nm). The neff value of LP01 for whole wavelength range also satisfies waveguide propagation criteria $n2 \leq neff \leq n1$. Simulation results in Fig. 3 shows that at 850nm, $\eta eff = 1.4563$, at 1310 nm, $\eta eff = 1.4490$ and $\eta eff = 1.4453$ at 1550 nm window. As shown in Fig 2, electric field amplitude profile of LP_{01} mode has only one single peak in positive z-direction.

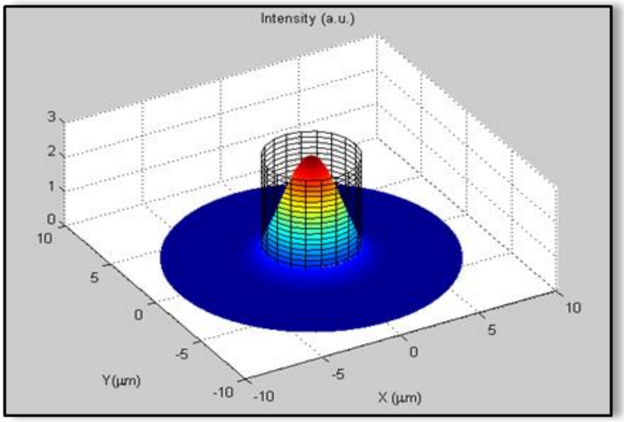

Fig. 2: Electrical field amplitude Plot for LP_{01}

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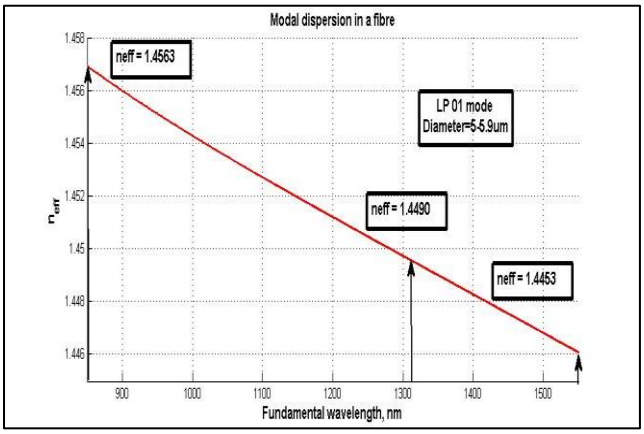

Fig 3: Modal dispersion curve of LP_{01} mode for diameter =5µm − 5.9 µm

As core diameter value increases from 5.9 µm another mode LP_{11} was observed trough fiber core along with basic LP_{01} mode. For diameter value of 6 µm, 7 µm, 8 µm, 9 µm, V-parameter ranges form V=2.408 to 3.8317 that results in the generation of LP_{01}= HE_{11} and LP_{11}= HE_{21}, TE $_{01}$, TM_{01} modes through fiber core.

Fig 4 shows that LP_{11} is guided mode till 850nm for diameter value of at-least 6µm with LP_{11}ηeff = 1.4539 at 850nm window

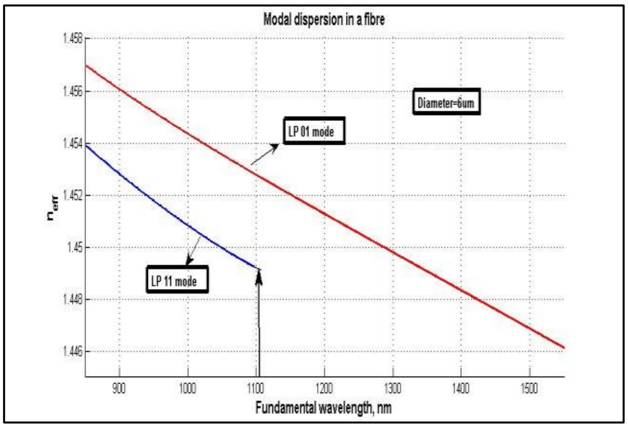

Fig 4: Modal dispersion curve of LP_{11} mode for diameter =6µm

To cover 1310 nm window diameter value should be increased up to 8μm as shown in Fig 5-6.

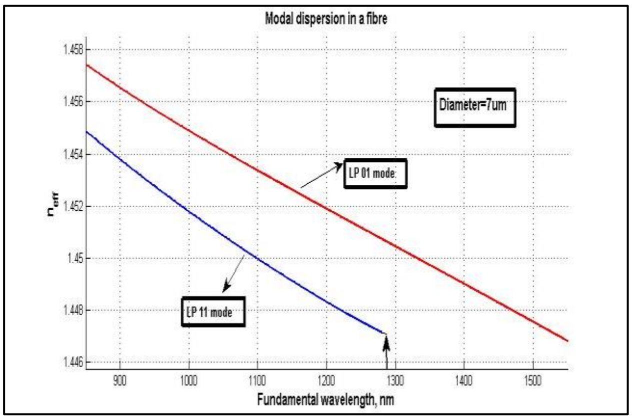

Fig 5: Modal dispersion curve of LP_{11} mode for diameter =7µm

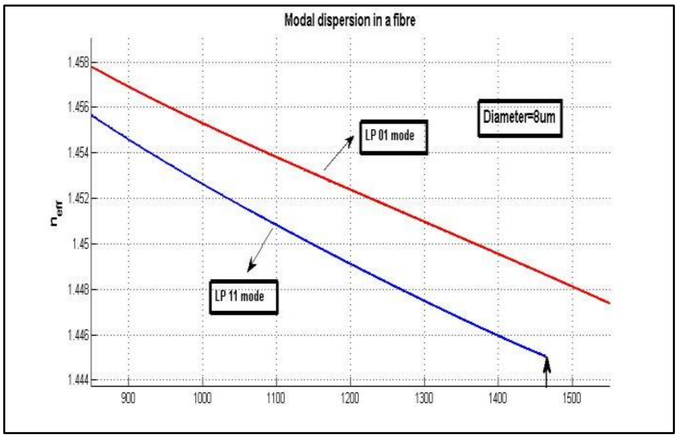

Fig 6: Modal dispersion curve of LP_{11}mode for diameter =8µm

Fig 7 shows that 9μm core diameter value results in to LP_{11} mode guidance through fiber core along with LP_{01} mode up to 1550 nm window with LP_{11} ηeff = 1.4562 at 850nm, $LP_{11}\eta eff$ = 1.4881 at 1310 nm and $LP_{11}\eta eff$ = 1.4443 at 1550 nm.

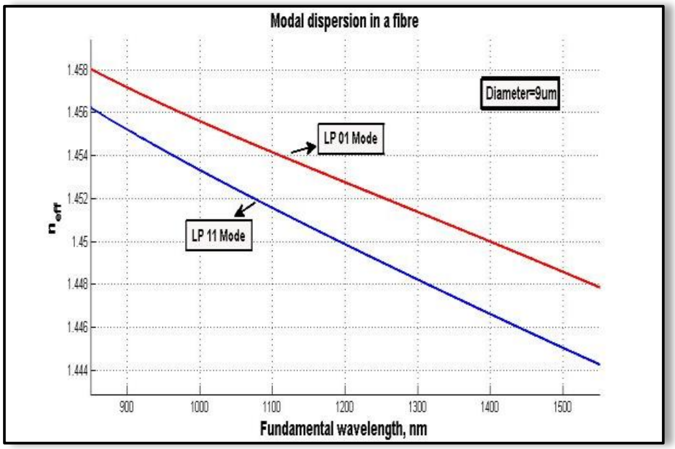

Fig 7: Modal dispersion curve of LP_{11}mode for diameter =9μm

By further increasing core diameter values up to 18 μm LP_{21}, LP_{31} and LP_{12} were guided along with LP_{01} and LP_{11} modes through same fiber core area. Tables 1-3 show the value of wavelength up to which respective modes can be guided for core diameter values.

Table 1: LP_{21} mode guidance range in wavelength w.r.t diameter values

LP_{21} Mode Generation

Diameter (μm)	Wavelength(nm)
10	1150
11	1270
12	1380
14	1550

Table 2: LP_{31} mode guidance range in wavelength w.r.t diameter values

LP_{31} Mode Generation

Diameter (μm)	Wavelength (nm)
13	1110
14	1200

16	1370
18	1550

Table 3: LP_{12} mode guidance range in wavelength w.r.t diameter values

LP_{12} Mode Generation

Diameter (μm)	Wavelength(nm)
14	1120
16	1275
18	1440

Fig. 8-11 shows the electric field amplitude profile for guided modes LP_{11}, LP_{31}, LP_{12} and LP_{21} respectively.

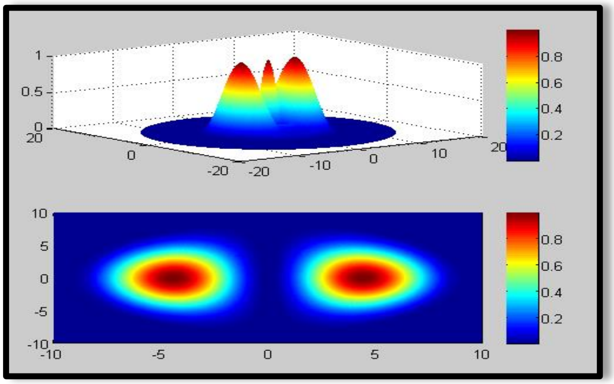

Fig 8: Electrical field amplitude plot for LP_{11}

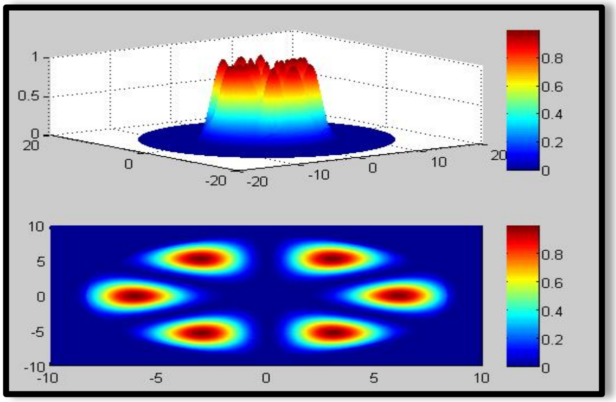

Fig 9: Electrical field amplitude plot for LP_{31}

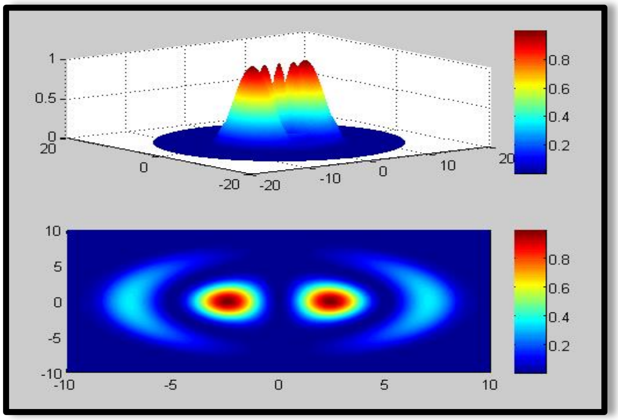

Fig 10: Electrical field amplitude plot for LP_{12}

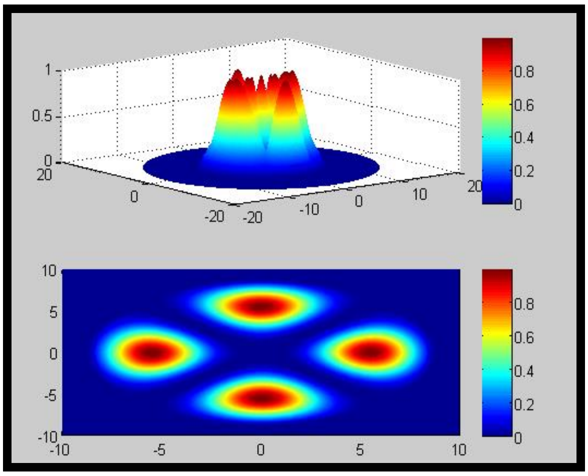

Fig 11: Electrical field amplitude plot for LP_{21}

3.2 Simulation Results for Nano-Fiber

Nano fibers are the special class of fiber having core diameter very small approximately of 100 nm to 1000 nm range. We investigated the modes that can be guided through such small core diameter at three standard telecommunication wavelengths. Due to core-clad index step size of .5 this is case of strong guidance approximation. Simulation results have shown that as the core diameter increases from 0.1 μm to 1 μm there is a gradual increase in $neff$ value for each guided mode. So, the maximum value is achieved at maximum core diameter value. But as the wavelength increases from 850nm to 1550 nm there is continuous decrease in $neff$ value for each guided mode. Parameters available in table 4 were kept constant for nano fiber simulations:

Table 4: Nano-fiber simulation parameter constants

Nano Fiber Simulation parameters

Refractive index Of core	1.544
Refractive index Of Clad	1
Material of Core	Silica
Core Diameter	.1 to 1µm

Simulation results, as in Fig. 12, shows that unlike weakly guiding approximation in nano-fiber HE_{21}, TE_{01} and TM_{01} are not so close to each other in their $neff$ profile so that they cannot be represented by single cure. At 850 nm following modes are guided through nano-fiber: HE_{11}, EH_{11}, HE_{21}, TE_{01} and TM_{01}. HE_{11} modes can be a guided mode through nano-fiber over its whole diameter range from 100 nm to 1000 nm ($0.1\ to\ 1\mu m$). HE $_{21}$ and TE $_{01}$ can be guided through nano-fiber only from .6 μm to 1 μm core diameter and EH_{11} can be guided through nano-fiber only from .98μm to 1μm core diameter.

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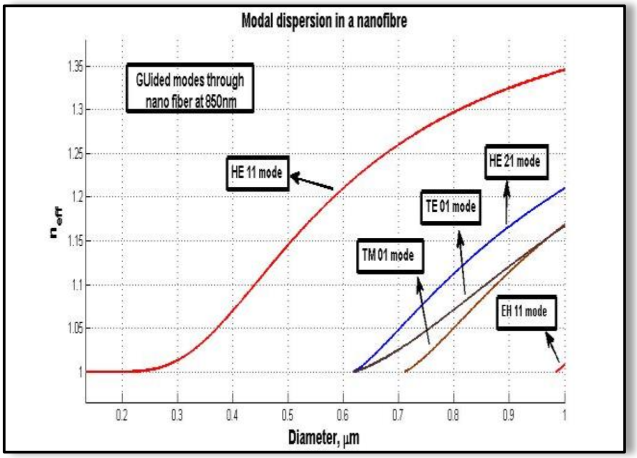

Fig 12: Modal dispersion curves of generated modes in nano-fiber at 850nm.

At 1310 nm HE_{11}, TE_{01} and $TM_{01}$are guided through nano-fiber. Simulation results, as in Fig. 13, show that at 1310 nm among the guided modes HE_{11} can be guided mode through whole nano-fiber core diameter range from 0.1 μm to 1μm and TE_{01} and TM_{01} can be guide through nano-fiber only from 0.96 μm to 1μm core diameter.

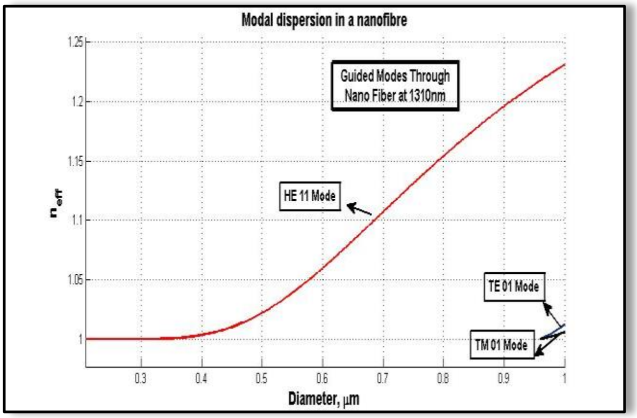

Fig 13: Modal dispersion curves of generated modes in nano-fiber at 1310 nm.

At 1550 nm only $HE_{11}$is guided through nano-fiber. Simulation result, as in Fig. 14, show that at 1550 nm only HE_{11} mode will be guided through nano-fiber. No other mode will be present at such small core diameter.

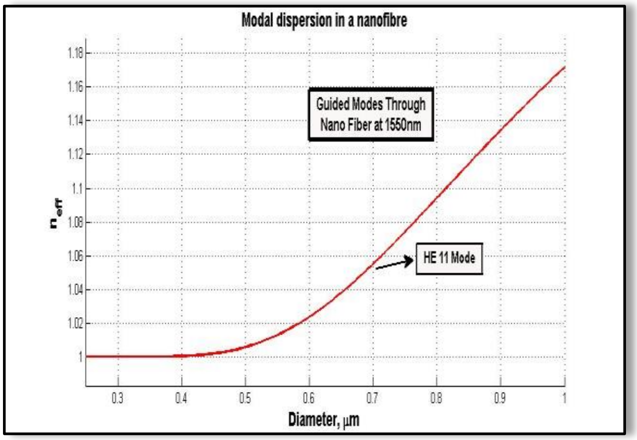

Fig 14: Modal dispersion curves of generated modes in nano-fiber at 1550 nm.

3.3 Simulation Results for Three Layer Fiber

Firstly, three-layer structure was designed by specifying fiber parameters. Then the modes guided through core and clad were investigated in exact two-layer model. Finally, a comparison between guided modes of exact two-layer model and Monerie, Tsao and Erdogan guided modes is presented. Following parameters were kept constant in three-layer guided mode analysis:

Table 5: Three-layer fiber simulation parameter constants

Three Layer Fiber Simulation parameters	
Refractive index Of core	1.455
Refractive index Of clad	1.45
Refractive index of Surrounding material	1
Material of Core	Silica
Core Diameter	5 µm
Clad Diameter	125µm

In exact two-layer method modes guided through core and clad are calculated as reference. Modes guided through core are calculated at three different standard telecommunication wavelengths 850 nm, 1310 nm and 1550 nm in each case only HE_{11} is guided mode through fiber core. It means that it is acting as SMF800, only single mode is guided through this fiber above 800nm wavelength. The simulation results in Fig 15, show that there is gradual increase in ηeff with increasing diameter and gradual decrease in ηeff with increasing wavelengths.

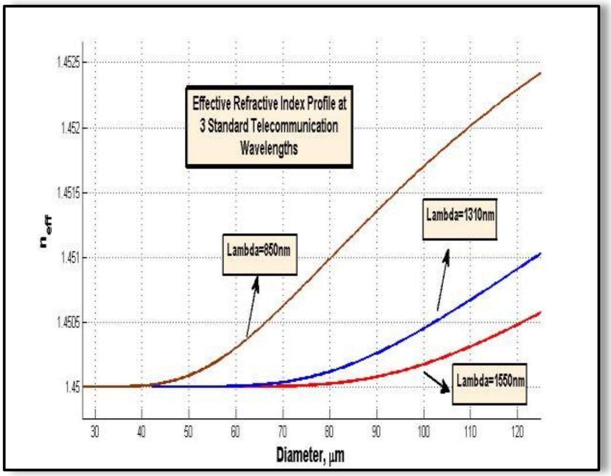

Fig 15: Core guided modes effective refractive index profile at 850nm, 1310 nm, 1550 nm

In exact two-layer model clad guided modes are HE_{11}, TE_{01} and TM_{01} as shown in Fig. 16.

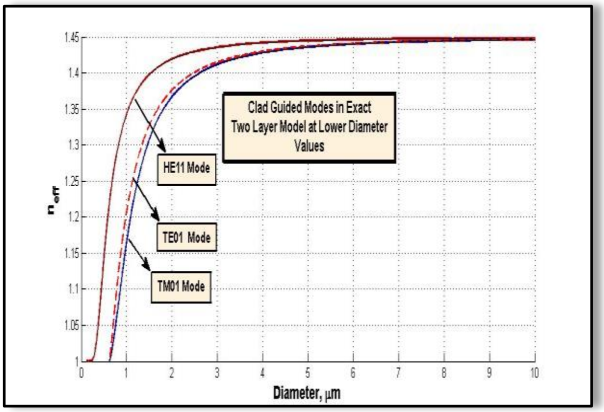

Fig 16: Clad guided modes refractive index profile at lower diameter values.

Computation of Monerie modes have resulted in to $MONERIE_{01}$ and $MONERIE_{11}$ modes. Simulation results in Fig 17 and 18, show that Monerie solution matches the exact solution in region of larger diameter. Curves in pink color are showing Monerie LP modes whereas curves in black are showing exact solution modes. LP_{01} mode fully deviates from HE_{11} mode, LP_{11} curve coincide with TE_{01} even for small diameters, TM_{01} do not match with Monerie approximation and at larger diameters Monerie and exact solution generated modes are same.

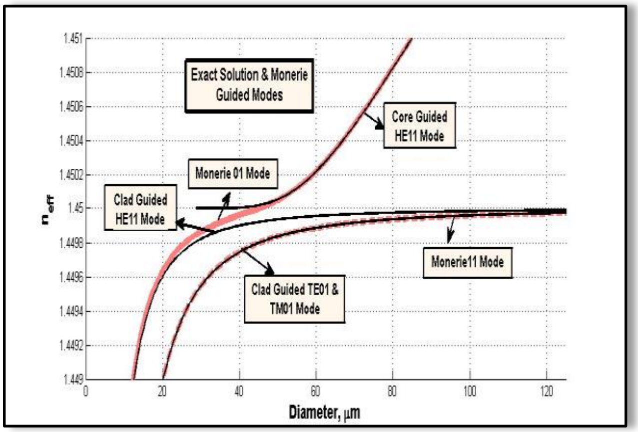

Fig 17: Exact two layer and Monerie generated modes comparison.

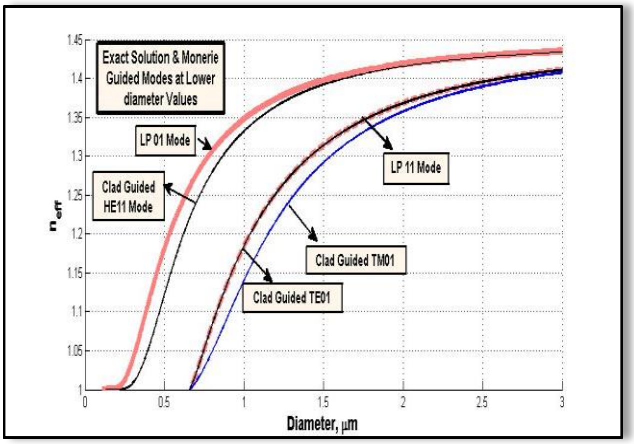

Fig 18: Exact two layer and Monerie generated modes comparison at lower diameter value

Simulations have shown that Tsao TE and TM modes accurately coincide with TE and TM modes at smaller diameter values but at larger diameter Tsao generated modes follows the Monerie LP_{11} modes. In Fig. 19-20, Curves in pink show Tsao LP 01 and LP 11 modes, curves in green are showing Tsao TE and TM modes and curves in Black are showing exact two-layer modes.

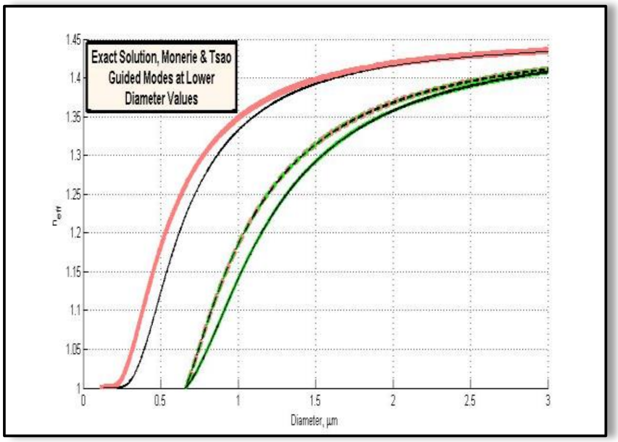

Fig 19: Exact two layer, Monerie and Erdogan generated modes comparison at lower diameter.

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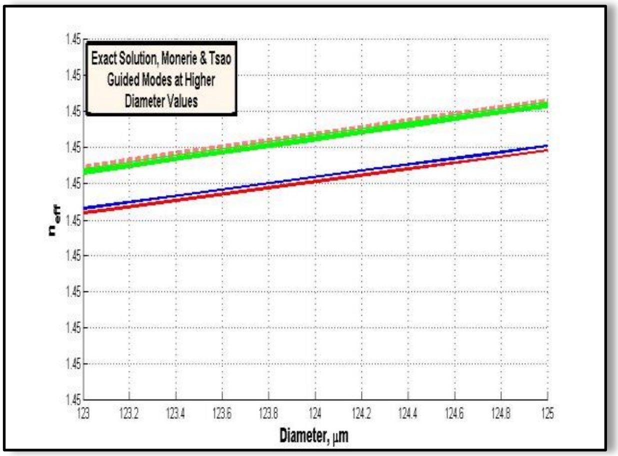

Fig 20: Exact two-layer Monerie and Tsao generated modes comparison at higher diameter values.

Simulation results in Fig. 21-22, have shown that Erdogan generated mode follows the exact solution HE_{11} mode at smaller diameter values. As the diameter increase it deviates from HE_{11} and follows LP_{01} Monerie mode. In Fig. 21, curves in pink show Tsao LP_{01} and LP_{11} modes, curves in green are showing Tsao TE and TM modes, curves in Black are showing exact two-layer modes and curves in Blue are showing Erdogan guided modes.

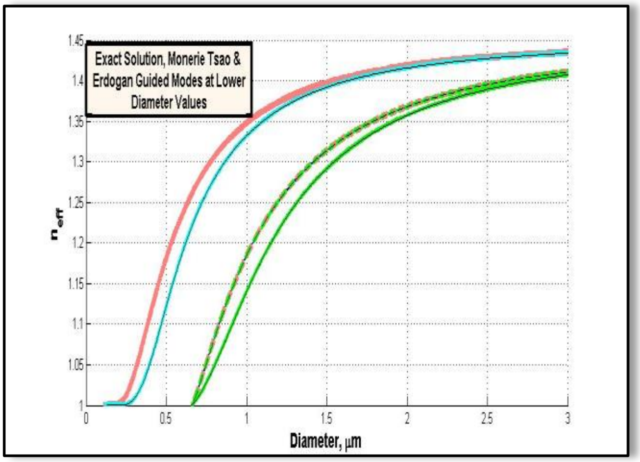

Fig 21: Exact Two Layer Monerie, Tsao and Erdogan generated modes comparison at lower diameter values.

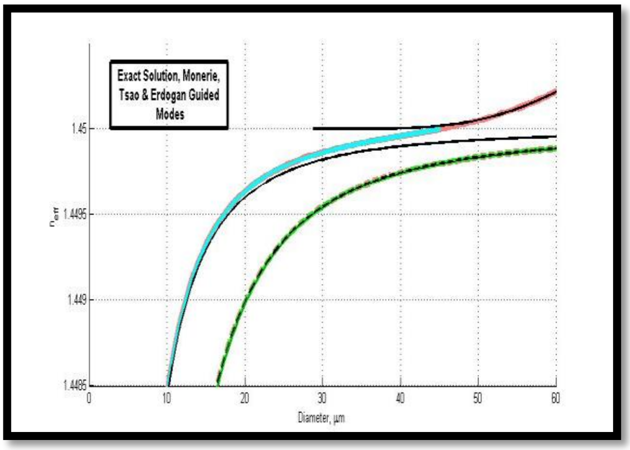

Fig 22: Exact Two Layer, Monerie, Tsao and Erdogan generated modes comparison at higher diameter values.

4. CONCLUSION

In this research work we have designed fiber core supporting LP $_{01}$, LP $_{11}$, LP_{21}, LP_{31} and LP_{12} simultaneously. So, by having five modes at the same time through fiber core high data rate requirement is satisfied. When multiple modes are simultaneously propagating through fiber core then modal dispersion or refractive index profile of each guided mode is the major limiting factor. So, we have investigated effective refractive index profile of each guided mode. Miniaturization is important demand for future technologies. So, nano-fiber is very promising research area of future communication networks due to its small core diameter. Through my research work I have investigated no of possible guided modes through nano-fiber at standard telecommunication wavelengths and their refractive index profiles against core diameter of 100 nm-1000 nm have been investigated. Some special cases of fiber communication are scenarios in which light is guided through fiber by cladding surrounding interface instead of core cladding interface such as tapered microfiber. To investigate such scenarios two-layer fiber is not sufficient so we have investigated three-layer fiber structures. Three different approaches for guided modes calculation through three-layer fiber have been simulated and the resulting guided modes and their refractive index has been compared with exact two-layer model.

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