International Journal of Electronics Communication and Computer Engineering
Volume 11, Issue 4, ISSN (Online): 2249–071X

An Analytical Simulation of Step-Index Single Mode Fiber using COMSOL and OptiFiber

Swastik Sahoo
IIT Bombay (Electrical Engineering), Mumbai, India.
Corresponding author email id: swastik@ee.iitb.ac.in

Date of publication (dd/mm/yyyy): 01/09/2020

Abstract **– This Paper is about simulating various results of Step Index Single Mode Fiber, where the standard parameters are according to that of OptiFiber. By varying core diameter and operating wavelength, Electromagnetic field domain analysis is being done in COMSOL. The result of both the simulations can be extended to other structure of Optical Fiber such as multi-mode step and graded index Fibers.**

Keywords **– COMOSL, OptiFiber, Surface Electric Field, Dispersion, Polarization Mode Dispersion, Mode Field Diameter, Losses.**

I. Introduction

Step index fiber is characterized by refractive index profile which is uniform throughout the core and will have step decrease in cladding. Step index fibers are mostly single mode which is defined by the way light is traveling through transverse mode in space and is expressed by Helmholtz Equation. The simulation analytics is divided into two parts, i.e. simulation through COMSOL, whereby varying the core diameter and wavelength, EM field pattern is shown which is followed by simulation through OptiFiber where the standard values are modified a little and the obtained simulations are discussed. This paper presents well-defined analysis about the core diameter and wavelength dependence of the single mode step index fiber.

In this study, mode analysis technique is used for the fiber where the three different values of core diameter is being taken, i.e. 2.5 µm, 4 µm and 6 µm at a fixed wavelength of 1550 nm. Then for Single mode fiber, taking fixed core radius as 4 µm, three optical windows are being taken, i.e. 850 nm, 1310 nm and 1550 nm. Core is taken as pure silica whose refractive index is 1.45 and that of cladding is Fused silica with a refractive index of 1.442. Transverse electric field, magnetic field, electric field displacement, polarization are studied for above cases. Then by taking core diameter as 4 μm and operating wavelength as 1550 nm, simulations are done through OptiFiber and the results are being discussed.

II. Background Study for COMSOL

In an Optical Fiber, light travels through total Internal reflection at the core-cladding interface. A fiber is characterized as a confined Optical Waveguide through which light propagates and depending on the number of rays, we will get discrete modes. Normalized frequency, V for a fiber is given by the expression:

$$V = \frac{2\pi a}{\lambda}\left(n_{core}^2 - n_{cladding}^2\right)^{0.5} \quad (1)$$

For a single mode fiber, this V-number value is 2.40. So, for an operating wavelength of 1550 nm, if back calculation will be done then radius of core can be calculated, which is 3.89 µm nearly equal to 4 µm. One value less than this standard value and one value greater than this is taken, i.e. 2.5 µm and 6 µm respectively. Three predefined optical windows which give minimum reflection and absorption are taken, i.

e. 850 nm, 1300 nm and 1550 nm.

In COMSOL Multiphysics, Electromagnetic wave and Frequency Domain (ewfd) is taken under Wave optics module and mode analysis is studied. The equation governing the transverse electric field is given by,

$$\nabla \times \nabla \times E - k_o^2 \varepsilon_r E = 0 \quad (2)$$

Where, k is the wave number and ϵ_r the relative permittivity. Simulations at different core radius with fixed wavelength and fixed core radius at different wavelengths are done and the results will be discussed further.

III. Theory for OptiFiber

For OptiFiber simulation, the Fiber theory is discussed here. Pure silica is taken as the host material whose bulk refractive index of 1.442 defines the same for cladding. By adding dopants as Germanium, refractive index is increased and that of core is defined to be 1.45. Linearly polarized mode of the fiber is studied here. Here theoretical cut-off wavelength is compared with the estimated ITU-T cut-off value. Cut-off wavelength is the maximum value beyond which there is no propagation.

If the refractive index of the material varies with operating wavelength, this causes group velocity to vary, leads to material dispersion. So, accordingly the group delay is expressed by the product of propagation distance with first frequency-derivative of propagation constant. This is shown as: $T_g = z\frac{d\beta}{dw}$. As core and cladding are having different refractive indices, so different optical wavelengths will propagate at different velocities. This is expressed by, $D(\lambda) = -\frac{\lambda z}{c} \times \sum_{i=1}^{N} \Gamma_i \frac{d^2 n_i}{d\lambda^2}$. Considering there are N number of layers and Γ represents the confinement factor for each layer. Waveguide dispersion is the distribution of energy due to different refractive indices of core and cladding region. This is expressed as: $D_{wg} == -\frac{\lambda z}{c} \times \frac{d^2 n}{d\lambda^2}$. Total dispersi--on is the combination of waveguide dispersion and material dispersion, expressed as: $D_{total} == -\frac{\lambda z}{c} \times \frac{d^2 n_{eff}}{d\lambda^2}$.

Polarization Mode Dispersion causes random spreading of optical pulses of two differently polarized light. Mode field diameter (MFD) is a representation of distribution of irradiance, i.e. Optical Power per unit area across the end face of a single mode fiber. The diameter at which, near field power falls to $\frac{1}{e^2}$ of its maximum value then it is called near field diameter (d_n) and same definition holds true for far field diameter (d_f). The expressions of these along with Effective mode area (A_{eff}) which is a quantitative measure of an area which a fiber mode effectively covers in the transverse dimensions and effective MFD (d_{eff}) are given as:

$$d_n = 2\sqrt{2}\left\{\frac{\int_0^\infty E^2(r)\, r^3 dr}{\int_0^\infty E^2(r)\, r dr}\right\}^{0.5} \quad (3)$$

$$d_f = 2\sqrt{2}\left\{\frac{\int_0^\infty E^2(r)\, r dr}{\int_0^\infty [E'(r)]^2\, r dr}\right\}^{0.5} \quad (4)$$

$$A_{eff} = \frac{[\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E(x,y)|^2\, dx\, dy]^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E(x,y)|^4\, dx\, dy} \quad (5)$$

$$d_{eff} = \frac{2}{\sqrt{\pi}} A_{eff} \quad (6)$$

E(x, y) represents the Optical Mode Field Distribution.

Bending Loss is the propagation loss, occurs in fiber due to bending. It is significant in large mode area fibers. When fiber bend radius is large compared to fiber diameter, that is called macro-bending and if small, then called micro-bending. Birefringence of a fiber is defined as the difference between the propagation constants of polarization eigen modes. It is expressed as: $\nabla\beta = \beta_x - \beta_y$.

Total loss in a fiber includes Material losses and Fiber induced Losses. Material loss is consisting of Rayleigh Scattering, UV and IR absorption, OH absorption losses. Rayleigh loss is inversely proportional to 4^{th} power of the wavelength, UV absorption results due to electronic absorption bands in UV region, OH absorption occurs because of overtones. Splice loss occurs due to any mismatch in refractive indices of two adjacent fibers. Assuming Gaussian mode field of single mode fiber, this loss will produce reflection and refraction of light. All simulations in OptiFiber are based on the above concepts and calculations.

IV. Results and Discussions

Figure 1-3 represents Normalized Electric Field for various core radius simulated in COMSOL Multiphysics. Depending on the value of the core radius, the value of Electric field will vary from the center towards the outer layer. Effective Mode index is given as 1.4419.

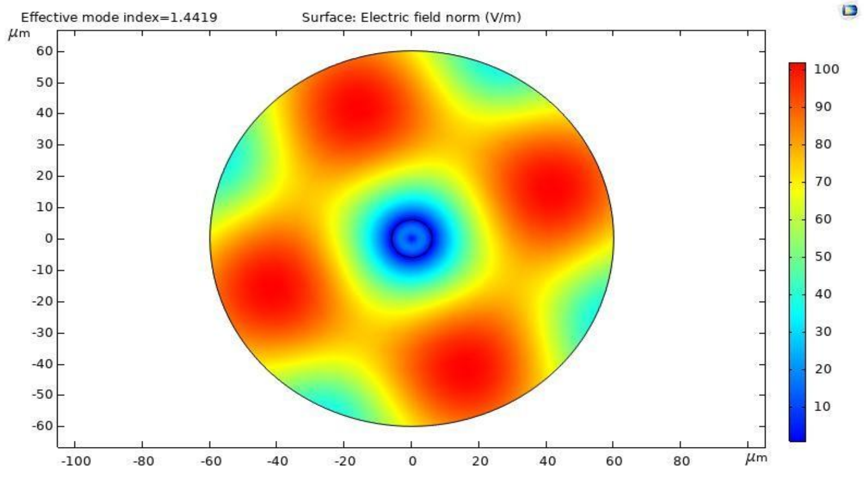

Fig. 1. Normalized electric field for the core radius of 2.5 μm.

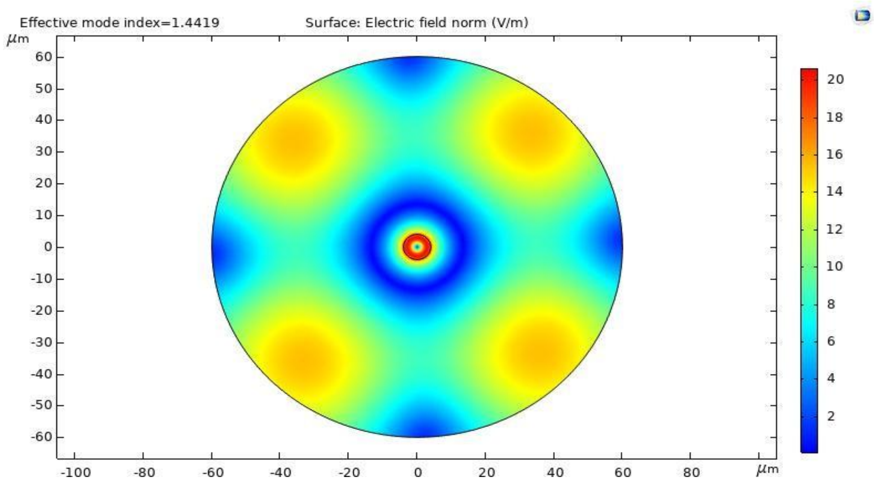

Fig. 2. Normalized electric field for the core radius of 4 μm.

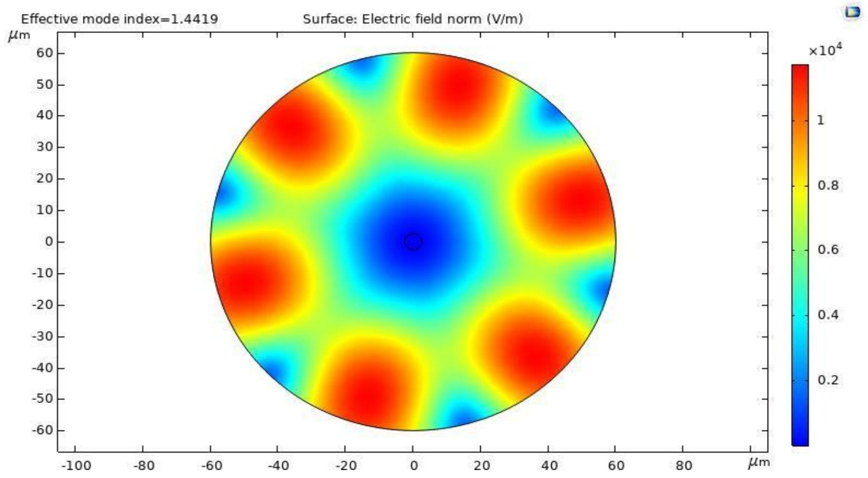

Fig. 3. Normalized electric field for the core radius of 6 μm.

Figure 4-6 represents Normalized Electric field along with contour for z-component of magnetic field for various core radius simulated in COMSOL Multiphysics. Figure 7-9 represents, Electric Field Displacement is proportional to the external Electric Field and it accounts for the effect of free and bound charge within the material. For various core radius Electric field Displacement is simulated in COMSOL Multiphysics.

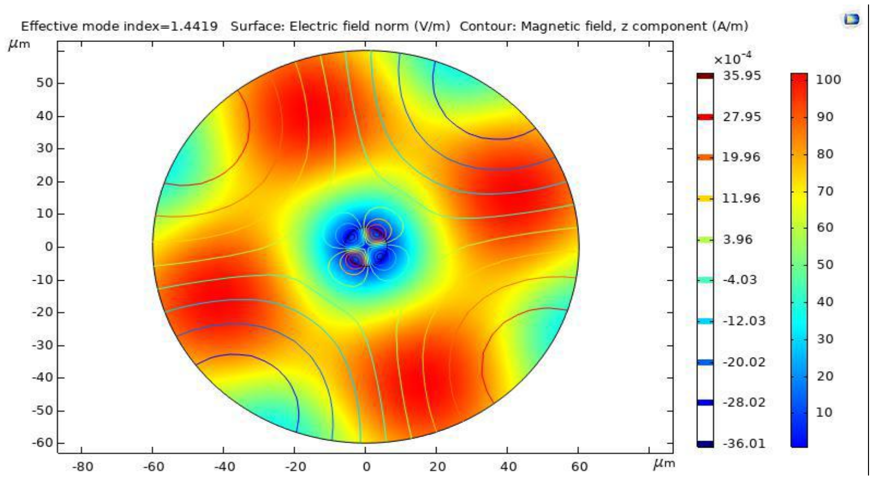

Fig. 4. Normalized electric field with contour of magnetic field for the core radius of 2.5 μm.

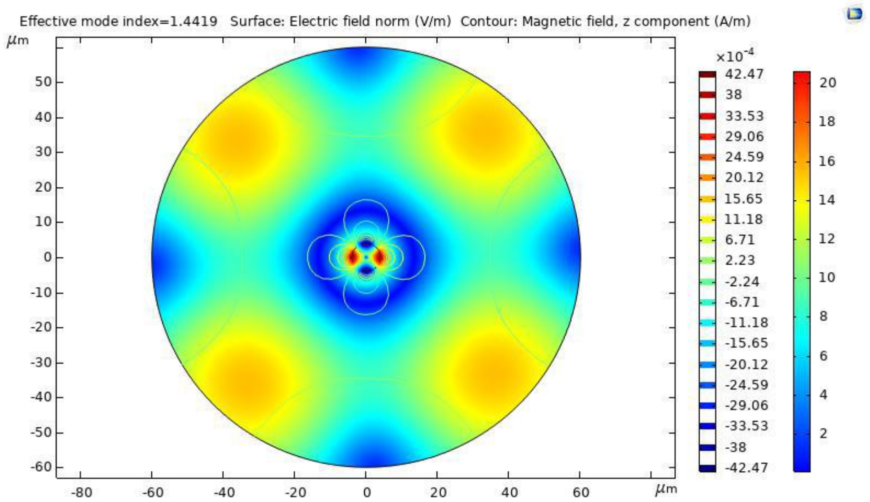

Fig. 5. Normalized electric field with contour of magnetic field for the core radius of 4 μm.

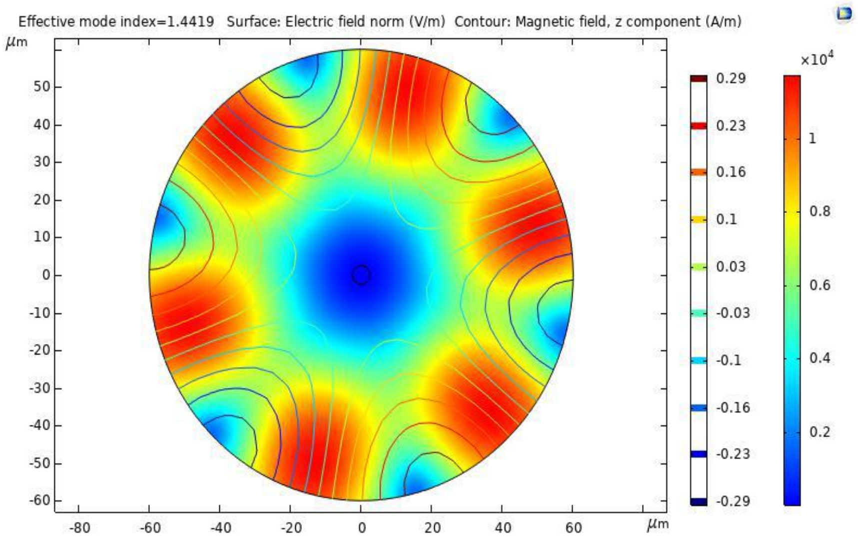

Fig. 6. Normalized electric field with contour of magnetic field for the core radius of 6 µm.

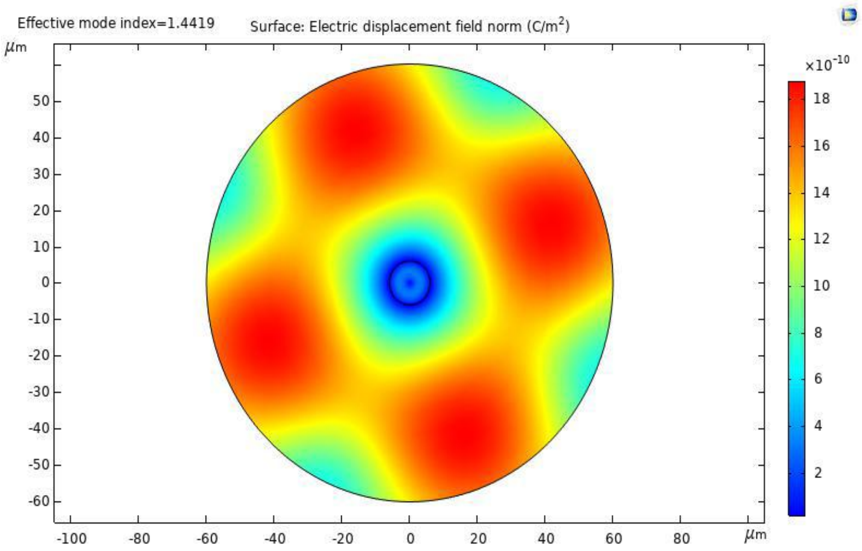

Fig. 7. Electric Field Displacement for the core radius of 2.5 µm.

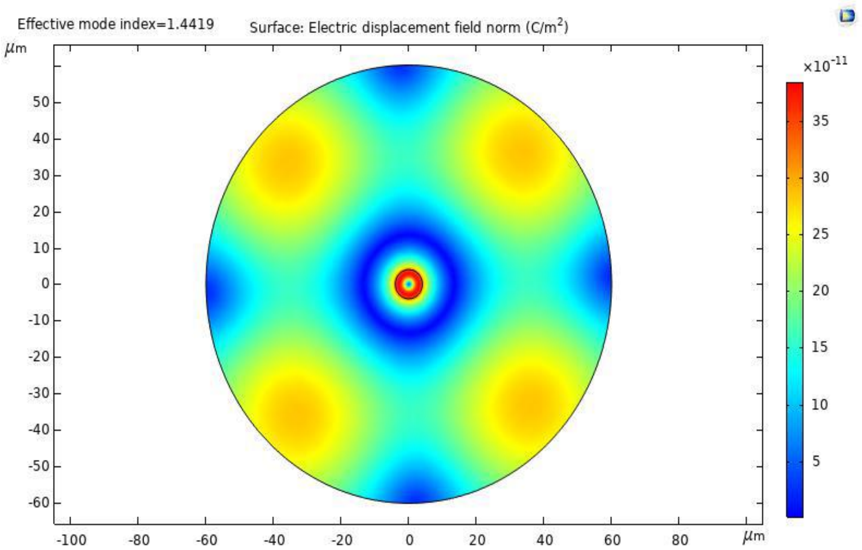

Fig. 8. Electric Field Displacement for the core radius of 4 µm.

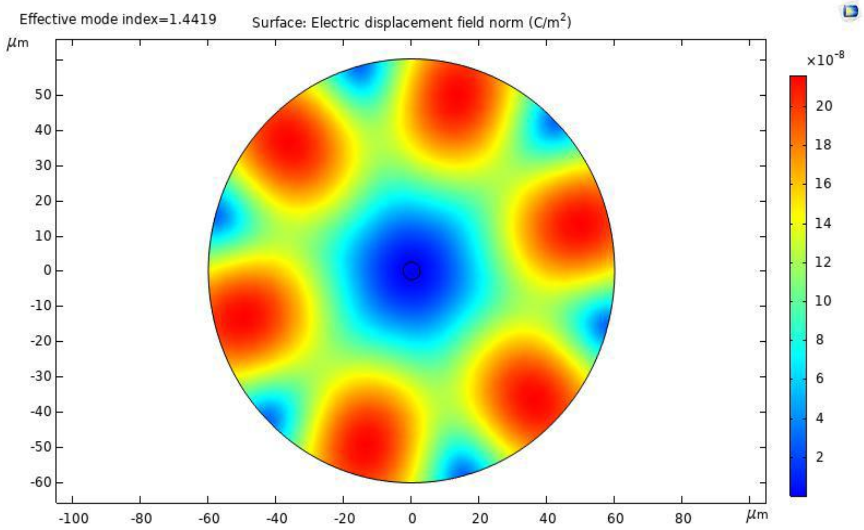

Fig. 9. Electric Field Displacement for the core radius of 6 µm.

Again, simulated normalized electric field is shown for three different optical windows, i.e. for 850 nm, 1300 nm and 1550 nm respectively. COMSOL Multiphysics based simulations are shown in figure 10-12.

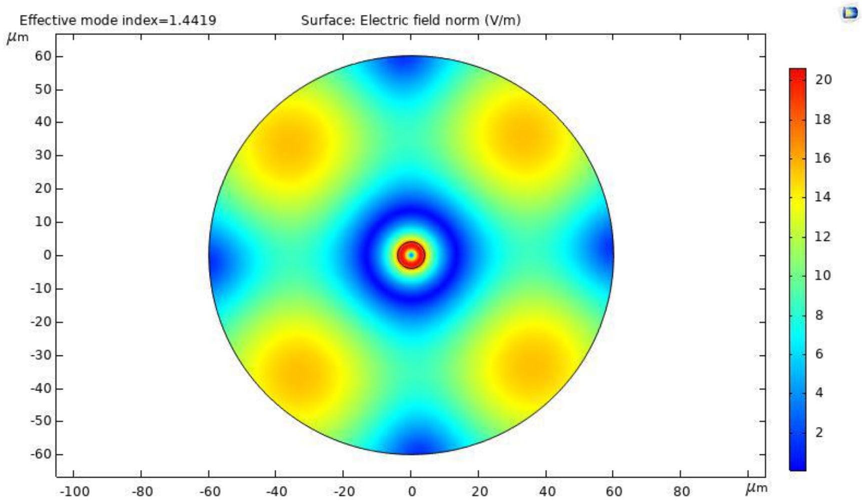

Fig. 10. Normalized Electric Field for a core radius of 4 µm at 850 nm.

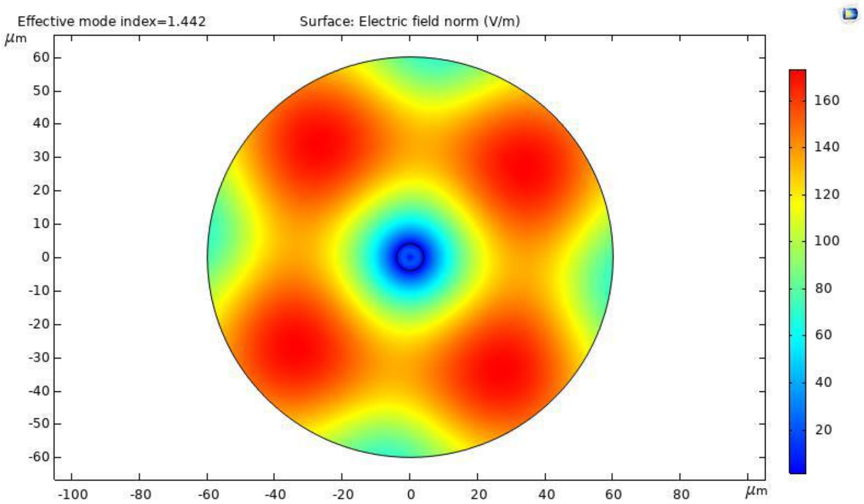

Fig. 11. Normalized Electric Field for a core radius of 4 µm at 1300 nm.

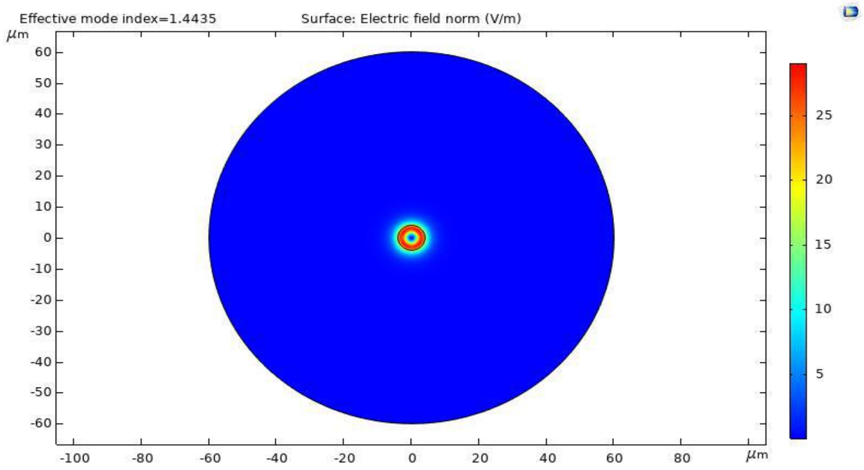

Fig. 12. Normalized Electric Field for a core radius of 4 µm at 1550 nm.

Now coming to simulations performed by OptiFiber for the core radius of 4 µm and the wavelength of 1550 nm. By calculating mode option, it will generate several results which are discussed below. The step index profile is given in figure 13. From the diagram, it is evident that core refractive index is 1.45 and that of cladding is 1.442.

Accordingly, relative refractive index is given as: $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$. By calculating, same value of 0.55 is obtained as the simulated value.

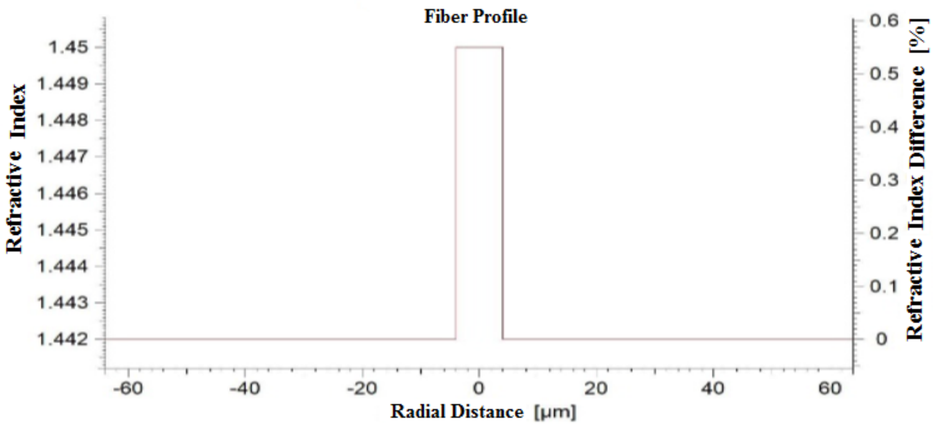

Fig. 13. Step Index Fiber Profile.

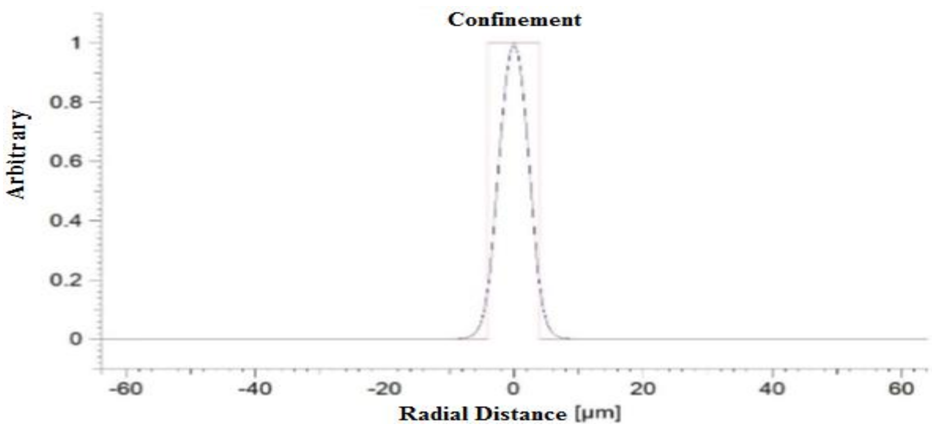

Fig. 14. Optical confinement of a step index single mode fiber.

The above diagram shows the percentage of mismatch for the index profile between ideal one and real one. The transition from cladding to core is not so sharp and also peak is not flattened.

Coming to Linearly Polarized (LP) mode. Fiber can support TE Mode, TM mode as well as Hybrid modes, but the difference between refractive indices of core and cladding is so small that, all the modes are degenerate and it is apparent to use single notation for all the above modes. $LP_{l,m}$ is the only mode where, l and m indicates number of radial and azimuthal zeros for a particular mode. Single mode fiber will support the fundamental LP (0, 1) mode which is shown below:

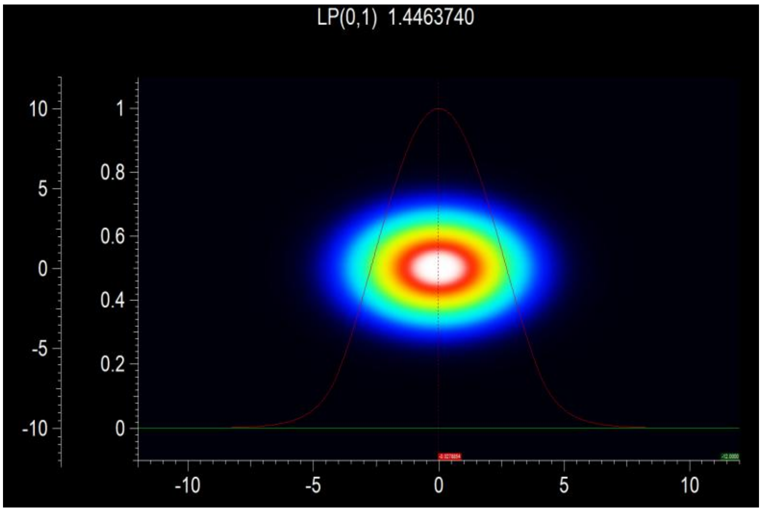

Fig. 15. LP (0, 1) Mode profile.

From this mode, theoretical wavelength is 1.58 μm given by ITU-T and calculated one is 1.49 μm. Modal index and Group index are shown below:

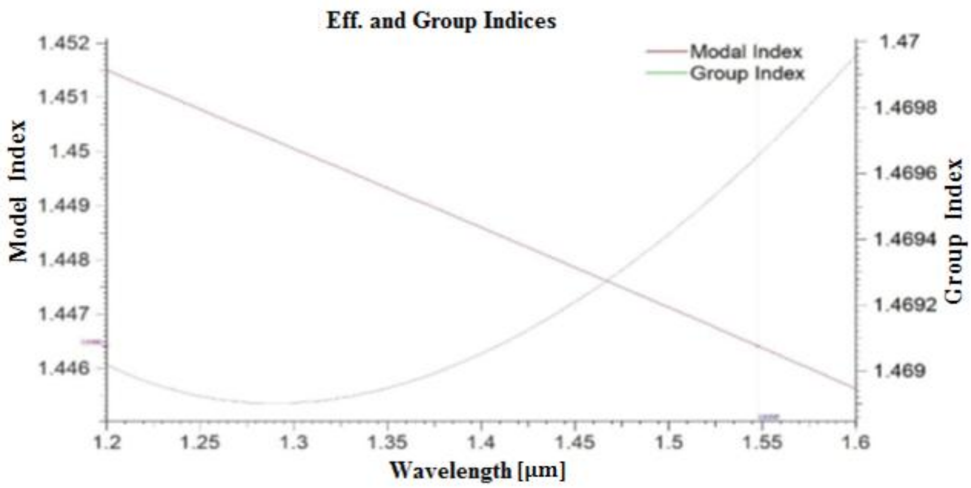

Fig. 16. Effective and group Indices of Single mode step index fiber.

Above diagram shows modal index reduces linearly as we go on increasing the wavelength, whereas group index shows non-linear behaviour.

Different refractive indices of core and cladding will result in propagation of light in different velocities leading to group delay and dispersion. They are shown in Figure 17 and figure 18 respectively. Group delay is expressed in ps/Km and Dispersion is measured in ps/Km-nm, since it expresses temporal spread (ps) per unit propagation distance (Km) per unit pulse spectral width (nm). Dispersion increases with wavelength and zero dispersion is at 1.29 μm wavelength.

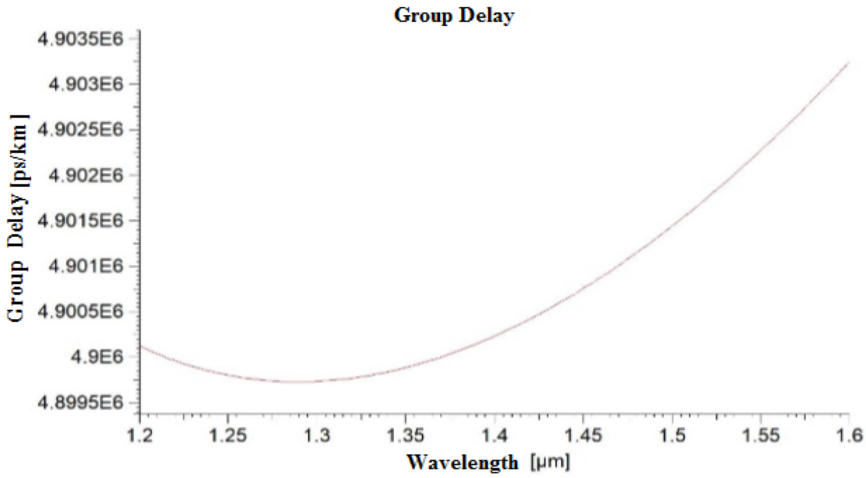

Fig. 17. Group Delay of single mode step index fiber.

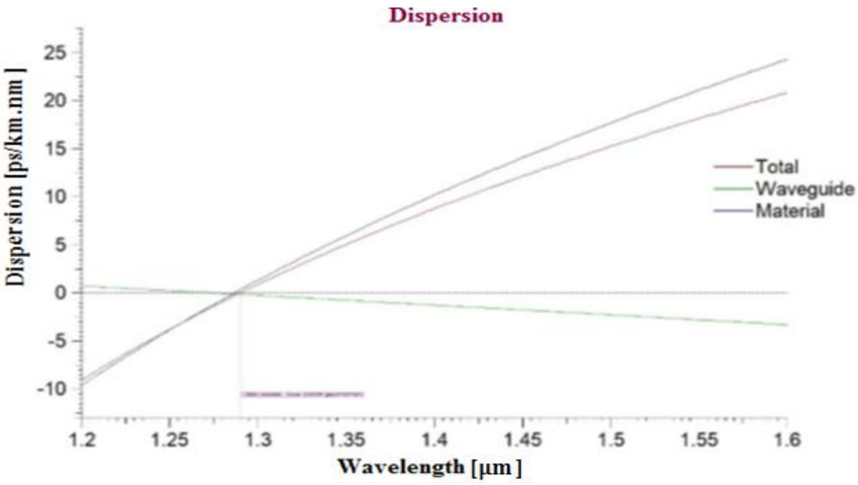

Fig. 18. Dispersion of Single mode step index fiber.

The effective mode field diameter and Polarization mode dispersion are shown in figure 19 and figure 20 respectively.

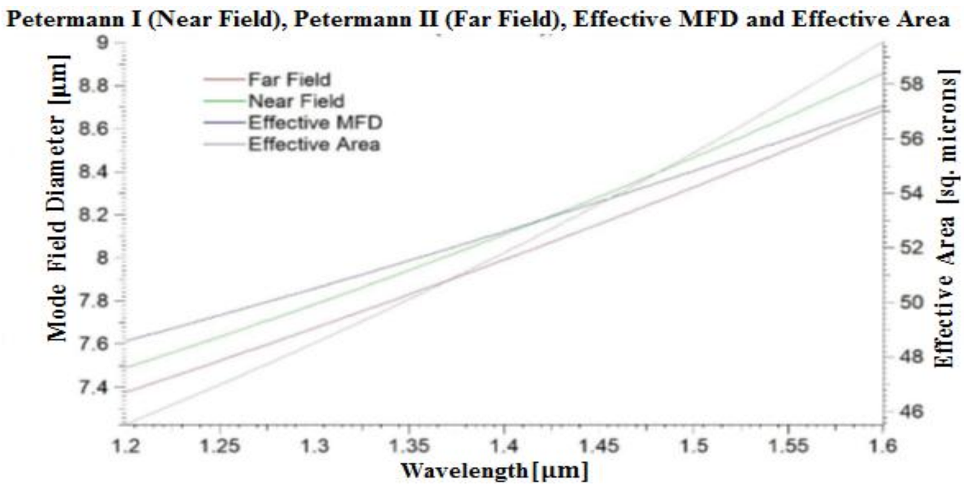

Fig. 19. Near Field, Far Field, Effective area and effective MFD of Single mode step index fiber.

All the factors are increasing with wavelength. Near field diameter is having a higher value than far field. Effective MFD at 1550 nm is around 8.2 µm which is greater than the core diameter of 8 µm.

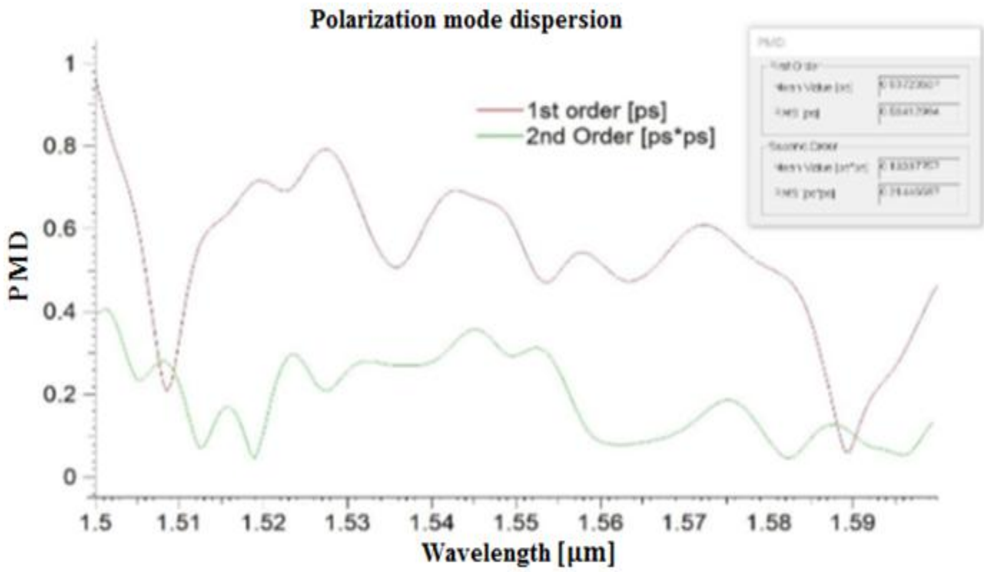

Fig. 20. Polarization Mode Dispersion of single mode step index fiber.

Plot above shows a large density of peaks and valleys. PMD occurs due to non-circularity of core. Impact of first order PMD depends upon differential group delay and the relative intensities of polarized light. If all the propagating lights are in same state of Polarization, then impairment is negligible. First order PMD can be mitigated but the amount of improvement in data rate is limited by the unmitigated effects of second order PMD. Bending loss is shown below:

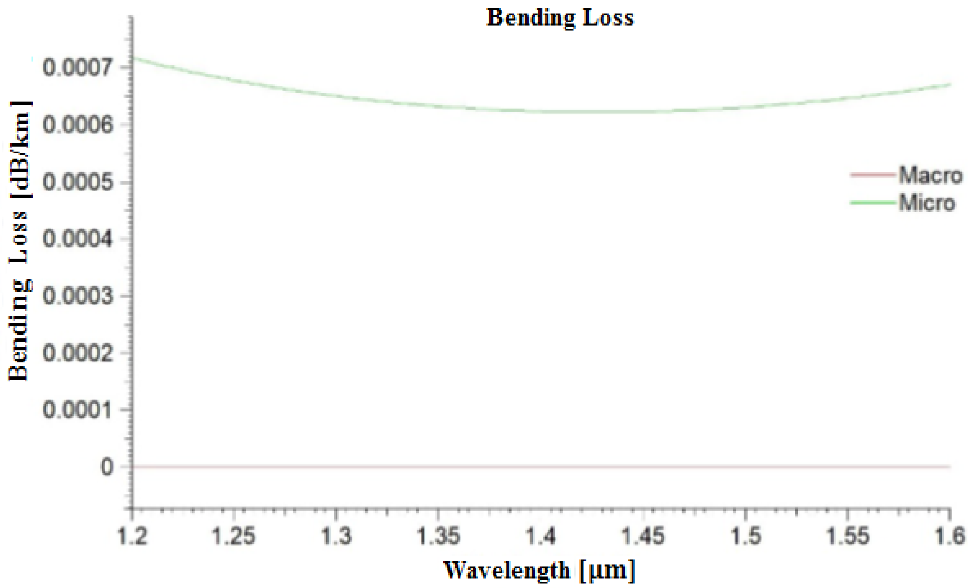

Fig. 21. Bending loss of single mode step index fiber.

As the core diameter is small, macro-bending doesn’t affect and its value is zero throughout. Negligible amount of micro-bending occurs.

Material loss as discussed above is shown in figure 22. Attenuation is around 0.2 dB/Km around 1550 nm and Rayleigh scattering reduces with increase in wavelength.

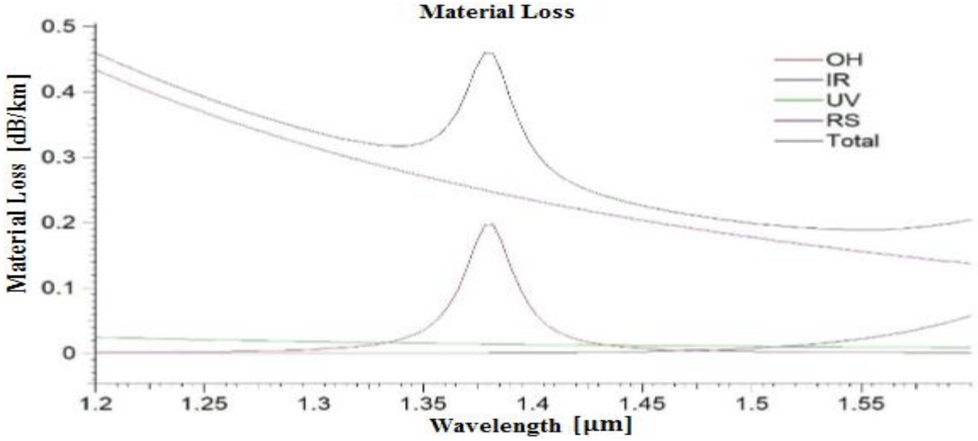

Fig. 22. Material loss of Single mode step index fiber.

Splice loss for the fiber is shown in figure 23. Transverse and longitudinal splice losses are dominant one. Transverse losses deals with x and y direction. Longitudinal loss is between the design of micro-optical components such as lens-less inline filters, micro-mechanical switches. Angular loss is due to misalignment between two fibers.

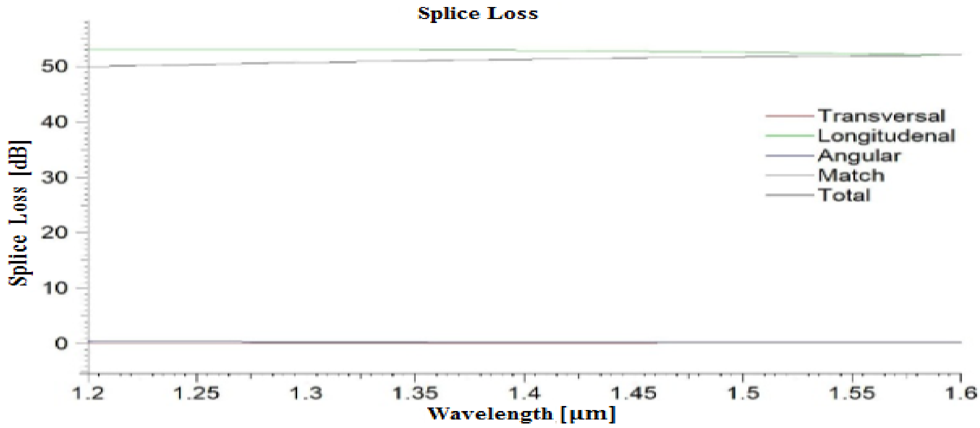

Fig. 23. Spice loss of single mode step index fiber.

Birefringence of the fiber is shown in figure 24. Here, $\Delta\beta$ represents the propagation constant difference and that is constant throughout the wavelength region. Differential Group Delay (DGD) is change in $\Delta\beta$ with respect to angular frequency. It increases in negative direction as wavelength increase. It is a measure of transit time difference between the light launched in fast axis to that in slow axis.

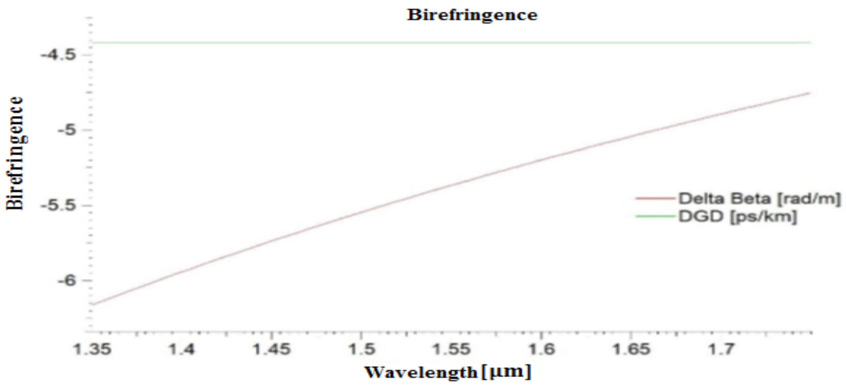

Fig 24: Birefringence of Single mode step index fiber.

V. CONCLUSION

An easy way but vast analysis of single mode step index profile is presented here. Overall, on the basis of simulation results given by COMSOL and Optifiber different parameters for a single mode step index fiber is studied and well analysed. These results give deep insight into the fiber and much knowledge can be gained. Further, other parameters of the fiber can be changed and simulations can be obtained and studied. Fiber structures can also be changed to multi-mode, graded index, bent fibers etc and the simulations can be performed.

ACKNOWLEDGMENT

The author is thankful to Indian Institute of Technology, Bombay to give licensed version of COMSOL and to Electrical Engineering Department for the continuous motivation and support.

REFERENCES

[1] Md. S.A. Bhuiyan, H.M.M.R. Mondal, An analytical approach of defining best single mode fiber by analysing the fiber performance with subtle core diameter variation, IEEE, 978-1-4799-0400- 6/13@2013.
[2] Md. S.A. Bhuiyan, Design, Simulation, performance analysis and optimization process of MMGRIN fiber with RI distribution@ ECERE, 2014.
[3] A. Nechibvute, C. Mudzingwa, Modelling of Optical Waveguide Using COMSOL Multiphyiscs, IJERT, ISSN: 2278-0181, Vol 2, Issue 5, May-2013.
[4] G.S. Kliros, J. Konstantinidis, C. Theraskias, Prediction of Macrobending and Splice Losses for Photonic Crystal Fibers based on the Effective Index Method.
[5] https://www.fiberoptics4sale.com/blogs/archiveposts/95048070-basic-optics-for-optical-fiber
[6] https://www.fibercore.com/expertise/fiberpaedia/differential-group-delay-dgd
[7] https://www.sciencedirect.com/topics/computerscience/fiber-dispersion
[8] https://www.fiberoptics4sale.com/blogs/archive-posts/95052294-optical-fiber-attenuation
[9] https://www.photonics.com/Articles/Polarization_Mode_Dispersion_Concepts_and/a25153
[10] https://www.rpphotonics.com/encyclopedia.html
[11] https://www.ad-net.com.tw/material-dispersion-waveguide-dispersion-polarization-mode-dispersion/
[12] https://optiwave.com/optifiber-manuals.
[13] https://doc.comsol.com/5.5/doc/com.comsol.help.comsol/COMSOL_ReferenceManual.pdf
[14] https://komunikasioptik.wordpress.com/2013/03/22/modal-analysis-of-step-index-single-mode-fiber-optic-using-comsol-multiphysics-4-3/

AUTHOR'S PROFILE

Swastik Sahoo, Research Scholar in Electrical Engineering, IIT Bombay, India. He has received his M. Tech degree in E&ECE department at IIT Kharagpur, India. email id: swastik.sahoo79@gmail.com