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# Waveguide based sensor for NPK nutrient detection in soil

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***ABSTRACT:****In agriculture, Soil testing has been around for years, and is commonly used to determine if nutrients are sufficient for crop growth and optimal yield. The macronutrients such as nitrogen (N), phosphorus (P) and potassium (K) required for on-field testing, should be both cost-effective and re-usable. In this paper, we have simulated optical waveguides based sensor, which is widely known for its high sensitivity and ease of implementation in optoelectronic devices. Each of the NPK macronutrients has different absorption wavelength, therefore the waveguide design is based on high penetration depth of evanescent wave in the sample region. The high sensitivity of optical waveguides along with the concept of absorption wavelength is used to design a waveguide structure for sensing concentration of NPK nutrients in the soil. The structure suggests that the simulated device is feasible to fabricate. The study shows the maximum absorption at wavelength near 635nm for potassium nutrient in soil and it is experimentally verified.*
***KEY WORDS:****Waveguide, NPK, Soil, Evanescent, Macronutrients, Absorption, Sensor*

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## I. INTRODUCTION

In agriculture, there are few nutrients like Nitrogen, Phosphorus and Potassium which are found in higher concentration as compared to other nutrients. These are hence known as NPK macronutrients in soil. The NPK nutrients highly affect the fertility of the soil. It becomes very important to detect the concentration of these nutrients in soil, as then the amount of fertilizer to be added can be accurately studied [1]. In the current age of technology, the use of optoelectronic devices as sensors has provided a way for manufacturing of cost effective and highly sensitive sensors. Optical waveguides offer several distinct advantages when it comes to high transmission of light waves. Waveguides can be used for integration with opto-electronic components for compactness. The modal profiles of waveguides depend on the refractive indices of the materials used in designing the waveguide. This offers more flexibility in designing as compared to optical fibers. Optical waveguides allow a guided wave to propagate within its core. The two main regions of an optical waveguide are the core and the cladding. The guided light wave propagates through the core of the waveguide and the cladding allows the confinement of the wave within the core. Optical waveguides support multiple modes of transmission of the guided wave. The propagation constant of these modes is defined by the effective refractive index of the system of cladding and core of the waveguide. The use of optical waveguides as a sensor provides high sensitivity. It also supports high selectivity of targeted nutrients with the use of single mode waveguides. In this paper, we study the design of an optical waveguide sensor which uses single mode transmission for detecting NPK nutrients in soil samples. The sensor is based on the concept of absorption of light by the targeted nutrient.

### *1.1 Absorption Wavelength of NPK nutrients*

The absorption of light by the targeted nutrient as studied in [2], gives us absorption wavelength of the NPK nutrients as shown in table 1.

***Table I*. Absorption Wavelength of NPK nutrients**

| Nutrient | Absorption Wavelength (nm) |
|---|---|
| Nitrogen | 470 |
| Phosphorus | 540 |
| Potassium | 640 |

### *1.2 Working of the waveguide*

The waveguide sensor is roughly modelled as shown in figure 1. The soil sample is mixed with deionized water and kept on top of the waveguide as seen in figure 1.

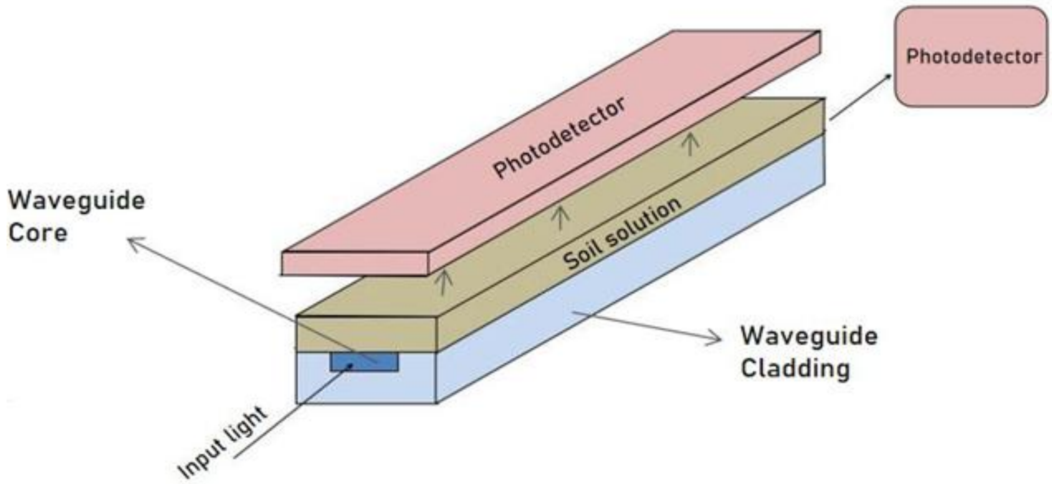


**Figure 1: Model of waveguide sensor**

The input light to the waveguide has a wavelength equal to the absorption wavelength of the targeted nutrient. When light propagates through the waveguide using total internal reflection, at each reflection an evanescent wave propagates in the sample medium, perpendicular to the interface between the core and the sample medium. This wave is an exponentially decaying wave within the sample solution. The penetration depth of this evanescent wave within the sample solution depends on the effective refractive index of the waveguide[3]. This penetration depth (d) multiplied with the number of reflections on the sample-core interface will give us the optical path length (b). We can obtain a relation between Absorbance (A), optical path length and concentration of nutrients using Beer Lambert's law (equation 1) [7].

$A = Ebc$……………………………..……............................…..(1)

*where, E = Attenuation coefficient, b = optical path length, c = concentration of nutrient*

A photodiode is kept on the output face of the waveguide and another photodiode is used to monitor the light coming out from the top of the sample region of the waveguide as seen in figure 1. This allows us to obtain the intensity of light (I) passing through the waveguide, as well as the light left unabsorbed from the evanescent wave. Using intensity of transmitted light at the output (I) and input incident light intensity ($I_o$), we can calculate the absorbance (A) by the sample[10].

*Transmittance (T)* = $\frac{I}{Io}$……………………………..……............................…..(2)

*Absorbance (A)* = $log_{10}(\frac{1}{T})$……………………………..……............................…..(3)

Using equation 1 and equation 3, we can find the concentration of the targeted nutrient. Since the waveguide has a thin core, a number of waveguides can be merged together in an array to form a wider sensor with better coverage for the soil sample.

## II. MATERIAL AND METHODS

The simulation of the waveguide is carried out on the FIMMWAVE software. The waveguide has a total width of $5.2\mu m$and a height of $4\mu m$. The material used for the core of the waveguide is Polymethyl methacrylate (PMMA) ( RI ~ 1.49 ) and for the cladding region we use Cytop ( RI ~ 1.34 )[3]. PMMA is used as the core of the waveguide because it supports high transmission of light and also since it has a high refractive index. With the core having a refractive index higher than the cladding region, it allows good confinement of light throughout the waveguide. The cladding used has a lower refractive index in order to allow higher penetration depth of evanescent waves within the cladding region. In figure 2 we can see the materials used in the waveguide simulation.

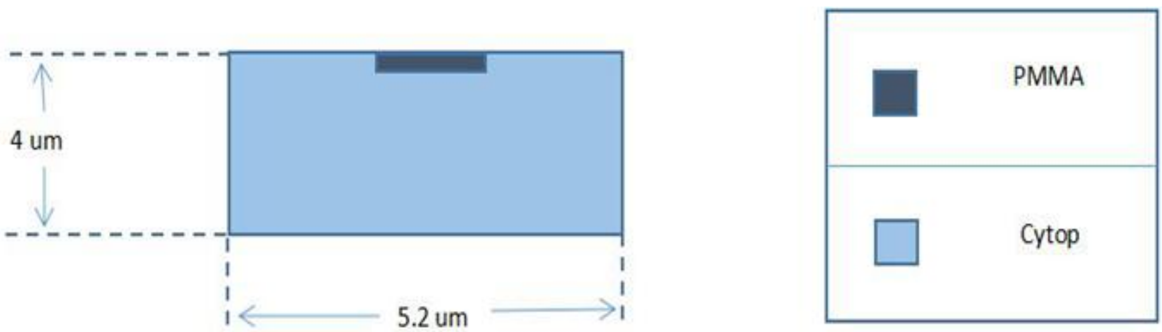


**Figure 2: Materials used for simulated waveguide**

### *2.1 Verifying the absorption wavelength of Potassium*

Hydroponic solutions contain nutrients mixed in water to be used as fertilizer for plants. The hydroponic solutions from CityGreens are used for our experiment. We use a hydroponic solution of Potassium to verify the absorption wavelength of Potassium [2] using a 635nm wavelength laser source at 1mW power. The hydroponic solution of potassium is kept in a cuvette as shown in figure 3.

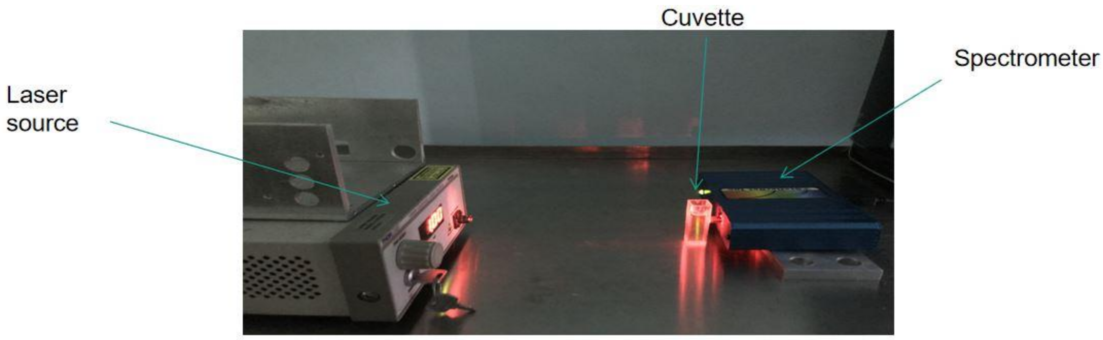


**Figure 3: Setup of the experiment**

The laser light passes through the cuvette and falls on the spectrometer. The spectra for Potassium, Nitrogen and Phosphorous hydroponic solutions are taken for 635nm of laser light as input. The spectra obtained is as seen in figure 4. It is seen that the potassium hydroponic solution shows high absorption of 635nm light as compared to the nitrogen and phosphorus hydroponic solution. The reading for cuvette has been taken to verify that there is minimal absorption of light arising due to the cuvette in the wavelength range of the light source.

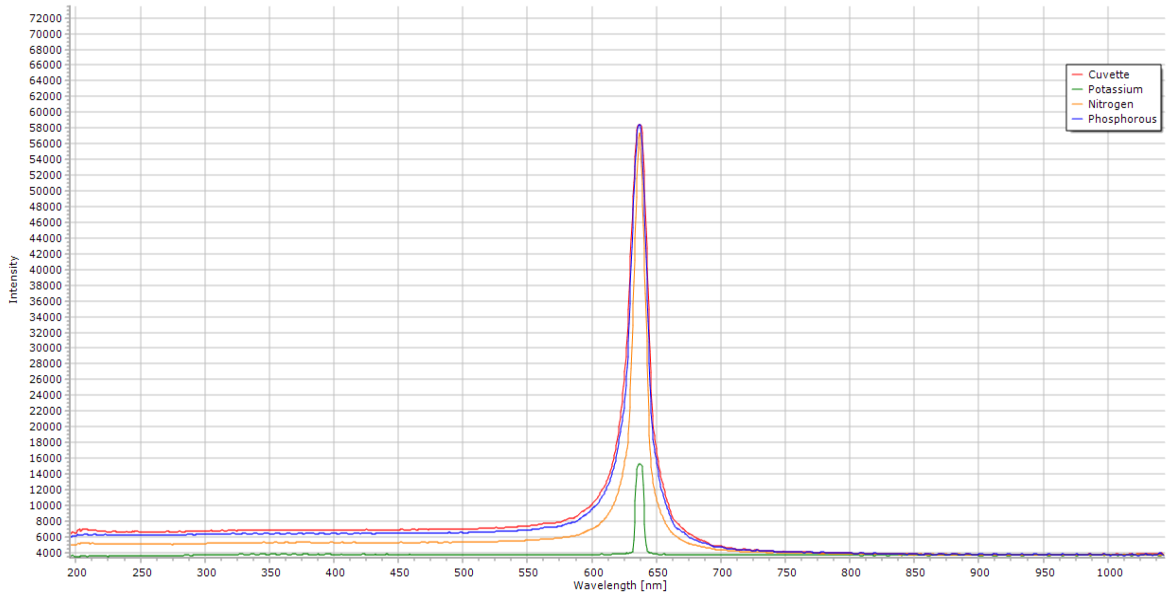


**Figure 4: Intensity of light after passing through Hydroponic NPK solutions**

The setup is as shown in figure 3. The cuvette is filled with 1mg of soil sample and 3ml of deionized water. The spectra for this is as seen in figure 5, 6 and 7 with spectra labelled as 'Soil Only'. The soil samples are taken from three different places. The soil taken from the New garden shows higher absorption of light of the 635nm wavelength compared to the other two samples. To check whether we see an increase in absorption of light by addition of potassium nutrient in soil, we add the potassium hydroponic solution in the sample and take new readings. This spectra is labelled in figure 5, 6 and 7 as 'Soil+K'.

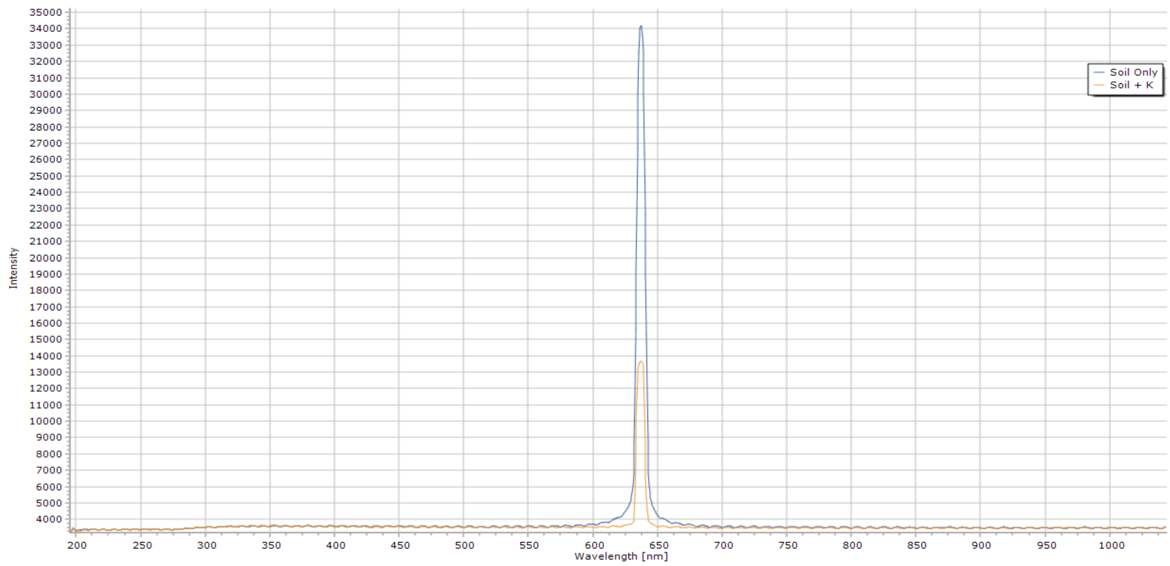


**Figure 5: Intensity of light after passing through soil sample 1 (Playground)**

For the second reading, we replace the deionized water in the cuvette with a hydroponic solution of potassium and note the spectra. Comparing both the spectra in figure 5, 6 and 7, we see that after adding the hydroponic solution in the soil sample, the concentration of potassium in soil increases and hence higher absorption of light occurs, leading to a drop in the intensity of light.

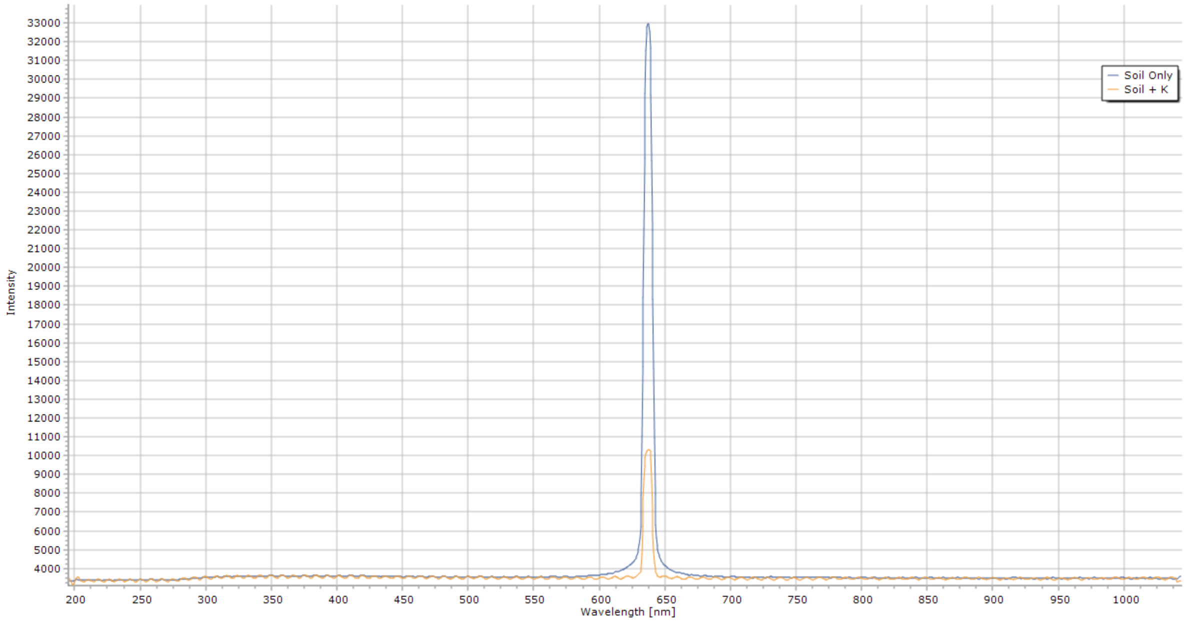


**Figure 6: Intensity of light after passing through soil sample 2 (Old Garden)**

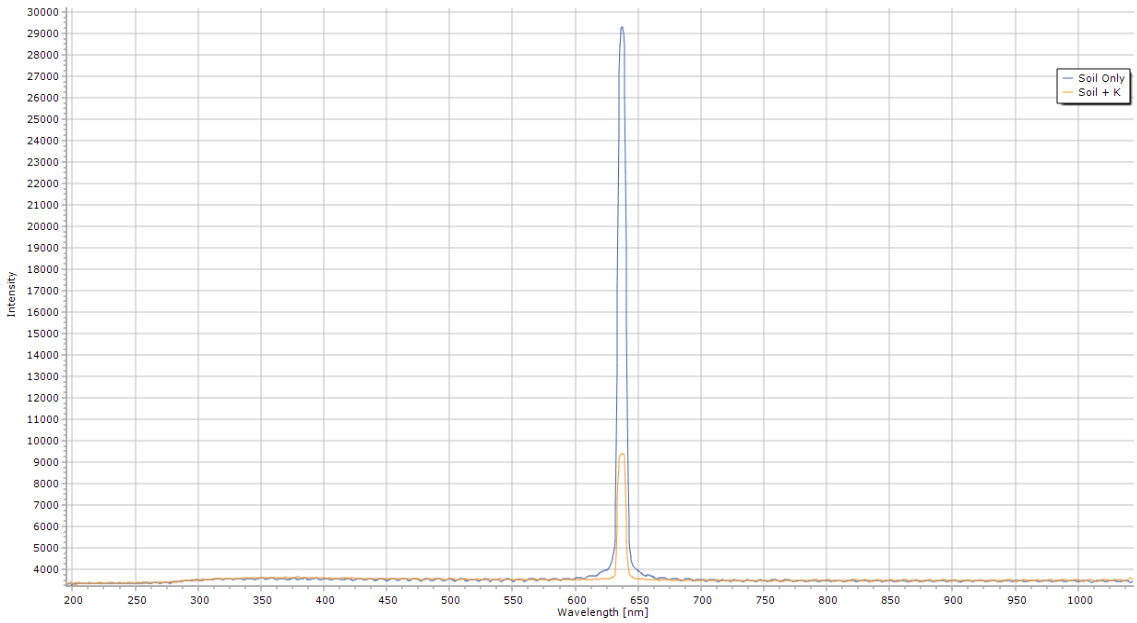


**Figure 7: Intensity of light after passing through soil sample 3 (New garden)**

From the observations noted using the spectra, we verify that the potassium nutrient in soil has absorption of light of wavelength near 635nm.

### 2.2 *Solving for waveguide modes using simulation*

The simulation for solving the waveguide modes is done on the FIMMWAVE software. The waveguide model is simulated as shown in figure 3. The input light for the simulated waveguide is taken with wavelength equal to the absorption wavelength of the targeted NPK nutrients. The TE mode of the model is studied, where there exists a wave propagating parallel to the interface between the sample and the core, and is exponentially decaying in the direction perpendicular to the interface. This wave is known as the evanescent wave. The penetration depth of the evanescent wave within the sample on top of the core can be calculated using equation 4.

$$d = \frac{\lambda}{2\pi}\frac{1}{\sqrt{neff^2 - ns^2}} \quad \ldots\ldots(4)$$

where, $\lambda$ = wavelength of input light, neff = effective index of waveguide mode, ns = refractive index of sample

Using the Finite Difference Waveguide mode solver, we determined the mode index for different core thicknesses. In this simulation, we look at the fundamental TE mode of the waveguide and note down the observations for the confinement factor, effective index of the waveguide and calculate the penetration depth of the evanescent wave using equation 4. We consider the fundamental mode because we aim to develop a single mode waveguide for the sensor, as it provides least attenuation as well as it will allow us to detect only the targeted nutrient. The core width is taken to be $0.4\mu m$to start with, as with the other size parameters and geometry of the waveguide, from $0.4\mu m$core width onwards the waveguide allows single mode transmission.

## III. RESULTS AND DISCUSSIONS

The plots seen in figure 7, figure 8 and figure 9 show the waveguide behavior for single mode transmission. The effective index, confinement factor and penetration depth in the case of the three different wavelengths 470nm, 540nm and 640nm is simulated and plotted against the core thickness of the waveguide.

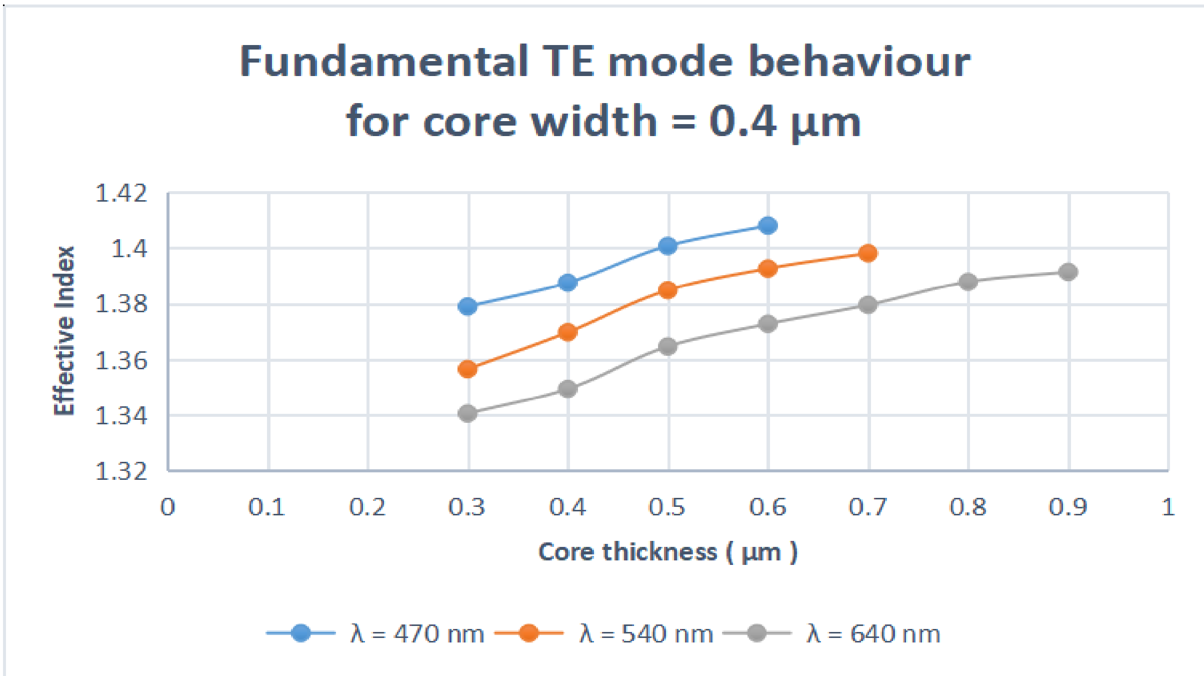


**Figure 7: Effective index vs Core thickness**

It can be seen in figure 7, that for fundamental TE mode, the effective index of the TE mode increases with increase in core thickness. We know that the effective index is the ratio of the propagation constant in the waveguide to the free space propagation constant. From this we can say that the propagation constant of the wave for the particular mode increases with increase in the core thickness.

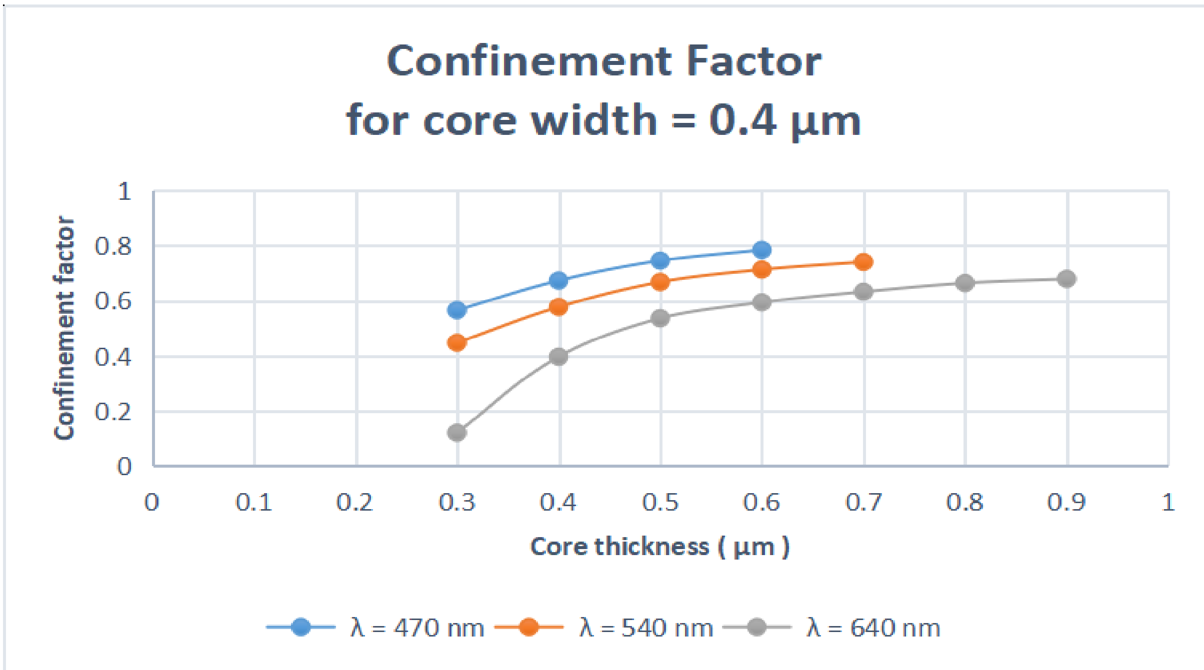


**Figure 8: Confinement factor vs Core thickness**

The confinement factor of the TE mode (figure 8) tells us how well the wave is confined within the waveguide for the particular TE mode. We see that the confinement factor increases with an increase in core thickness. For 0.3$\mu m$ we see the confinement factor of the 640nm light wave to be below 0.2, which is very a lossy mode.Hence, we neglect the 0.3$\mu m$core thickness for our waveguide and begin considering from 0.4$\mu m$onwards.

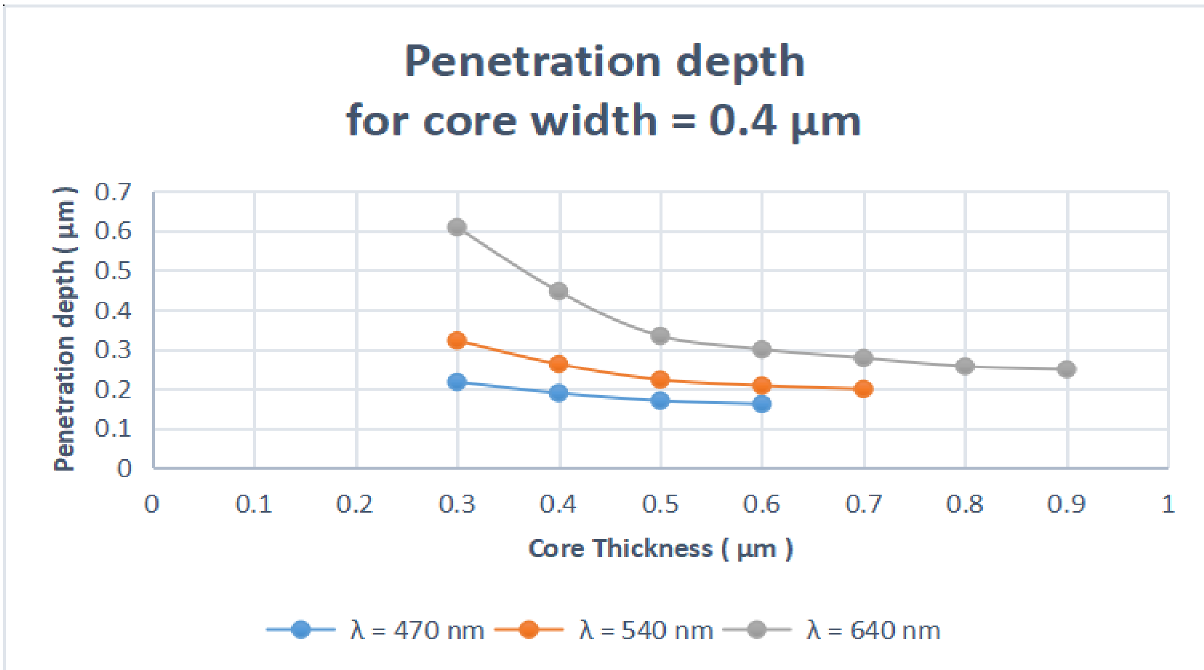


**Figure 9: Penetration depth vs Core thickness**

The figure 9 plot shows us that the penetration depth of the evanescent field decreases with increase in core thickness. The refractive index of the sample to calculate the penetration depth is taken as 1.33, as that of water, because the sample is soil mixed with deionized water which will have a refractive index close to that of water. This can be compared with figure 8 to see that as the confinement increases, the penetration depth of the evanescent wave decreases. As we have neglected the $0.3\mu m$core thickness from our previous case, we see that the penetration depth is highest for the $0.4\mu m$core thickness corresponding to the $0.4\mu m$core width of the waveguide.The penetration depth of evanescent wave for the three sources for the waveguide with 0.4 core width and 0.4 core thickness is given in Table 2.

***TableII*.Penetration depth for different wavelengths of input light**

| Wavelength of Input light (nm) | Penetration depth of evanescent wave (nm) |
|---|---|
| 470 | 189.3 |
| 540 | 262.6 |
| 640 | 446.9 |

## IV. CONCLUSIONS

We verified that the potassium nutrient in soil absorbs light of wavelength near 635nm. Based on the results of this study, we have simulated a waveguide which uses absorption of light by the NPK nutrients.It is seen that the penetration depth of the evanescent wave increases as we reduce the core thickness of the waveguide. If the core thickness is taken to be too low, the confinement factor of the mode drops very low. So we select a core thickness adequate in both the parameters. We see the penetration depth of the evanescent wave within the sample solution is between $0.1\mu m$ and $0.5\mu m$. Hence, we have simulated a waveguide sensor for detection of NPK nutrients in soil, based on the concept of absorption of light by the nutrients. The waveguide sensor uses the evanescent wave to be absorbed by the nutrient, in order to detect a drop in the total intensity of light through the waveguide.

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