Chapter 8
DISCUSSION OF RESULTS AND CONCLUSIONS
8. Discussion of results and Conclusion

The main features of the results obtained from the experimental studies are

8.1 For plastic optical fiber the optical power output decreases as the refractive index of the guiding medium (Palm oil) increases. This is evident from the fig 7.18, 7.19, 7.22 and 7.23. Similar trend is noticed with sunflower oil as the guiding medium. The variation of the power output with refractive index of the liquid which acts as cladding for the exposed portion, that is, sensing region is the main part of the experimental work and needs to be explained.

8.2 Again for a plastic optical fiber the decrease in output with increase in refractive index is dependent upon the wavelength of the propagating wave. For the same sensing length and same guiding medium (palm oil) it can be seen from figures 8.1, 8.2 and 8.3 that the power output decreases with increase in wavelength. For example it can be seen from the table 8.1; for a refractive index of 1.444 the output power at 820nm is -43.86 dBm where as in the case of 850nm it is -46.85 dBm for 1 cm core exposed. This is depicted graphically in fig. 8.1.

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>Output power (-dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>820</td>
<td>43.86</td>
</tr>
<tr>
<td>850</td>
<td>46.85</td>
</tr>
</tbody>
</table>

Table 8.1: Variation of output power with operating wavelength

8.3 Another variable is the dependence of the power output on the sensing length. It can be seen from table 8.2, in a plastic optical fiber for a wavelength of 820nm as the sensing length increases from 1cm to 1.5cm and further to 2cm, the power output varies from -43.86 dBm to -44.60 dBm, and further to -45.29 dBm at the same refractive index of 1.444.
Fig. 8.1: Graph showing refractive index of the guiding liquid (25ml adulterated palm oil) versus output power at 820nm and 850nm with cladding removed 1cm.
Fig. 8.2: Graph showing refractive index of the guiding liquid (25ml adulterated palm oil) versus output power at 820nm and 850nm with cladding removed 1.5cm.
Fig. 8.3: Graph showing refractive index of the guiding liquid (25ml adulterated palm oil) versus output power at 820nm and 850nm with cladding removed 2cm.
That is, for the same wavelength of the propagating wave and for the same refractive index, the power output decreases with increase in the sensing length.

<table>
<thead>
<tr>
<th>Sensing length (cm)</th>
<th>Power output (-dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43.86</td>
</tr>
<tr>
<td>1.5</td>
<td>44.60</td>
</tr>
<tr>
<td>2</td>
<td>45.29</td>
</tr>
</tbody>
</table>

Table 8.2: Variation of output power with sensing length at 820nm for plastic fiber

Again it can be seen from table 8.3, for the same plastic optical fiber operated at 850nm, as the sensing length is increased from 1cm to 1.5cm and further to 2cm, the output power varies from -46.85 dBm to -47.79 dBm, to -48.46 dBm. That is, again for the same plastic optical fiber operating at 850nm and for the same refractive index of 1.444, the power output decreases with increasing sensing length.

<table>
<thead>
<tr>
<th>Sensing length (cm)</th>
<th>Output power (-dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>46.85</td>
</tr>
<tr>
<td>1.5</td>
<td>47.79</td>
</tr>
<tr>
<td>2</td>
<td>48.46</td>
</tr>
</tbody>
</table>

Table 8.3: Variation of output power with sensing lengths at 850nm and refractive index 1.444 for plastic fiber.

8.4 For the same sensing length and refractive index of 1.444 the power output decreases with increase in wavelength, that is, for a sensing length of 1cm the power output for a wavelength of 820nm is -43.86 dBm Where as the power output for a wavelength of 850nm is -46.85 dBm which is illustrated in table 8.4. Similarly for a sensing length of 1.5cm the power output at a wavelength of 820nm is -44.6 dBm where
as power output for a wave length of 850nm is -47.79 dBm. For a sensing length of 2cm the power output for wave length of 820nm is -45.29 dBm where as the power output for wavelength of 850nm is -48.46 dBm which is illustrated in table 8.4.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Output power for core exposed (-dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1cm</td>
</tr>
<tr>
<td>820</td>
<td>43.86</td>
</tr>
<tr>
<td>850</td>
<td>46.85</td>
</tr>
</tbody>
</table>

Table 8.4: Variation of output power with exposed core in guiding medium at 820 and 850 nm.

For glass optical fiber the power output decrease as refractive index of the medium increases keeping the core of the fiber at 1cm, 1.5 and 2 cm and operated at 1300nm and 1500nm in guiding medium (Palm oil). Similar behavior is also observed for Sunflower oil. This is evident from figure 8.4, 8.5 and 8.6. Therefore it can be seen as far as the variation of the power output with refractive index of the medium is concerned the behavior follows the same pattern as that of the plastic optical fiber. However the rates of decrease of the power output with increase in refractive index are different for plastic fiber and glass fiber.

Rate of decrease of power output for 0.05 increases of refractive index of plastic fiber with sensing length.
Fig. 8.4: Graph showing refractive index of the guiding liquid (25ml adulterated palm oil) versus output power at 1300nm and 1550nm with cladding removed 1cm.
Fig. 8.5: Graph showing refractive index of the guiding liquid (25ml adulterated palm oil) versus output power at 1300nm and 1550nm with cladding removed 1.5cm
Fig. 8.6: Graph showing refractive index of the guiding liquid (25ml adulterated palm oil) versus output power at 1300nm and 1550nm with cladding removed 2cm.
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Output power for core exposed (-dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1cm</td>
</tr>
<tr>
<td>820</td>
<td>2.67</td>
</tr>
<tr>
<td>850</td>
<td>3.73</td>
</tr>
</tbody>
</table>

Table 8.5: Variation of output power with wavelength

Rate of decrease of power output for 0.05 increase of refractive index for glass fiber with sensing length.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Output power for core exposed (-dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1cm</td>
</tr>
<tr>
<td>820</td>
<td>3.23</td>
</tr>
<tr>
<td>850</td>
<td>3.60</td>
</tr>
</tbody>
</table>

Table 8.6: Variation of output power with wavelength

8.6 Power loss

Power loss is the difference between the power launched into the optical fiber and power collected at the second end of the fiber. When the cladding is not removed and for short lengths of the fiber, the power launched is the power collected at the second end of the fiber. In the sensing mechanism a short length of fiber is usually employed and as such, the attenuation in the fiber may be neglected. Thus, in the present case the power launched is measured as the [power output + attenuation when the cladding is not removed] in the normal fiber.

Thus

\[
[\text{Power Loss}] = \left[ \frac{\text{Power Launched}}{\text{into the Fibre}} \right] - \left[ \frac{\text{Power Collected at the}}{\text{second end of the Fibre}} \right]
\]
In the present set up again both plastic and (operated at 820nm and 850nm) and glass fiber (operated at 1300nm and 1550nm) are used. The experimental length of the fiber and the cladding portion removed is also same as before. Figures 8.7 represents the power loss versus density at a operating wavelength of 820 nm with palm oil as the guiding medium for plastic fiber for 1cm, 1.5cm and 2cm cladding portion removed. Fig 8.8 represents again the loss of power versus density of the guiding medium at an operating wavelength of 850nm when 1cm, 1.5cm, 2cm core of the plastic fiber exposed in palm oil.

The experimental arrangement remaining the same, the plastic fiber is now replaced with glass optical fiber and operated at wavelengths of 1300nm and 1550 nm with palm oil as the guiding medium. The length of the glass fiber being 10m and the core exposed to the guiding medium is again 1, 1.5, 2cm. Graphs drawn between the density versus power loss are represented in fig. 8.9 and fig. 8.10 when operated at 1300nm and 1550nm respectively.

From these graphs we notice that power loss in plastic fiber is more than in a glass fiber with the same guiding liquid in each of the above case. As mentioned earlier,

\[ \text{Power Loss} = \left[ \frac{\text{power launched into the fiber}}{\text{power collected at the second end of the fiber when a portion of cladding is removed}} \right] \]

Thus, the central problem is to find an explanation for loss of transmitted power when guiding liquid of varying refractive index acts as cladding, taking the normal attenuation of the fiber into account.

Figures 8.11, 8.12, 8.13, 8.14 indicates the power loss versus refractive index of the guiding medium for a plastic fiber operated at 820nm and 850nm and a glass fiber operated at 1300nm and 1550nm where the core portion is exposed to guiding medium of (palm oil) 1, 1.5, 2 cm
Fig. 8.7: Graph showing density of adulterated palm oil versus power loss at 820nm when 1cm/1.5cm/2cm core of plastic fiber exposed in adulterated palm oil.
Fig. 8.8: Graph showing density of adulterated palm oil versus power loss at 850nm when 1cm/1.5cm/2cm core of plastic fiber exposed in adulterated palm oil.
Fig. 8.9: Graph showing density of adulterated palm oil versus power loss at 1300nm when 1cm/1.5cm/2cm core of glass fiber exposed in adulterated palm oil.
Fig. 8.10: Graph showing density of adulterated palm oil versus power loss at 1550nm when 1cm/1.5cm/2cm core of glass fiber exposed in adulterated palm oil.
Fig. 8.11: Graph showing Refractive index of guiding liquid versus power loss at 820nm when 1cm/1.5cm/2cm core of plastic fiber exposed in 25ml adulterated palm oil
Refractive index of guiding liquid

Fig. 8.12: Graph showing refractive index of guiding liquid versus power loss at 850 nm when 1 cm/1.5 cm/2 cm core of plastic fiber exposed in 25 ml adulterated palm oil
Fig. 8.13: Graph showing refractive index of guiding liquid versus output power at 1300nm when 1cm/1.5cm/2cm core of glass fiber exposed in 25ml adulterated palm oil
Fig. 8.14: Graph showing refractive index of guiding liquid versus output power at 1550nm when 1cm/1.5cm/2cm core of glass fiber exposed in 25ml adulterated palm oil.
respectively. The pattern of the behavior of the power loss, the variation of the refractive index will follow the behavior of the power output.

8.7 Cutoff wavelength

Another important parameter for transmission of electromagnetic wave through a cylindrical wave guide is the cutoff wavelength. This parameter is a function of geometry of wave guide. When dealing with an optical fiber, the same concept is applicable, as a fiber becomes the wave guide and the optical radiation represent the electromagnetic wave. The cutoff wavelength for single mode transmission can be calculated from the relation

\[ \lambda_c = \frac{2\pi a}{2.405\left(\frac{n_i^2 - n_j^2}{n_i^2}\right)^{1/2}} \]

where 'a' is the diameter of the core,

\( n_i \) is the refractive index of core

\( n_2 \) is refractive index of cladding

The importance of cutoff wavelength is that modes having wavelengths larger than the cutoff wavelength cannot be transmitted as guided waves in optical fibers, i.e., only modes having lesser than cutoff wavelength are transmitted in the fibers as guided modes. All the modes having wavelength greater than the cutoff wavelength are transmitted as radiation modes and represent loss of power. Therefore, it is interesting to make a study of the observed power loss with cutoff wavelength as refractive index of the media which works as cladding for the exposed portion of the fiber is varying. Plots on the variation of the cutoff wavelength with observed power loss with variation in refractive index of plastic optical fiber and glass optical fiber of different operating wavelength with 1cm, 1.5cm, 2 cm core exposed in the guiding medium are presented in figures 8.15, 8.16, 8.17, 8.18.
A plot of the cutoff wavelength versus refractive index evaluated from the above expression is presented for each fiber in figure 8.19, 8.20. These graphs indicate the relationship for single mode transmission between refractive index of the guiding liquid and cutoff wavelength. It can be seen that in all cases there is a good correlation between power loss with variation of refractive index and cutoff wavelength for a single mode, i.e, as the power loss increases (with increase in refractive index) the cutoff wavelength decreases indicating the conversion of more and more guided modes into the radiation modes.

8.8 Normalized Frequency

The same phenomenon can also be represented in terms of normalized frequency, that is, V number. This is an important parameter connected with cutoff condition \[^{44}\] given by

\[ V = \frac{2\pi a}{\lambda} \left( n_1^2 - n_2^2 \right)^{1/2} \]

where ‘a’ is the diameter of the core,

- \( n_1 \) is the refractive index of core
- \( n_2 \) is refractive index of cladding

This is a dimensionless quantity and it determines how many modes a fiber can support. As V number decreases the number of guided modes supported by the fiber decreases and thus increase in the radiation modes which contribute to the power loss. It is reasonable to expect correlation between the observed power loss and the V number. Such correlations are presented in figures 8.21, 8.22, 8.23, 8.24 for various fibers operating at different wavelengths.
Fig. 8.15: Graph showing cut-off frequency versus power loss in plastic fiber at 1 cm/1.5 cm/2 cm core exposed in guiding liquid of various densities (adulterated palm oil) at 820 nm.
Fig. 8.16: Graph showing Cut-off frequency Versus Power loss in plastic fiber at 1/1.5/2 cm core exposed in guiding liquid of various densities (adulterated palm oil) at 850 nm.
Fig. 8.17: Graph showing cut-off frequency versus power loss in glass fiber at 1cm/1.5cm/2 cm core exposed in guiding liquid various densities of (adulterated palm oil) at 1300nm.
Fig. 8.18: Graph showing cut-off frequency versus power loss in glass fiber at 1 cm/1.5 cm/2 cm core exposed in guiding liquid of various densities (adulterated palm oil) at 1550 nm.
Fig. 8.19: Graph showing cut-off frequency versus refractive index in plastic fiber (palm oil)
Fig. 8.20: Graph showing cut-off frequency versus refractive index in glass fiber (palm oil)
8.9 Numerical Aperture

Numerical aperture of an optical fiber represents its light gathering power and is expressed \(^{[43]}\) by

\[ NA = \sin \theta_{\text{max}} = n_1 \sqrt{2\Delta} \]

As refractive index of the liquid changes amounting to the change in the refractive index of the cladding for sensing portion of optical fiber (where the cladding have been removed) the numerical aperture of this portion of the wave guide will also undergo a change in refractive index of the medium. Thus, as the refractive index of the medium increases and therefore light gathering power of this part of the optical fiber decreases. This is an alternate way of accounting the power loss suffered. A plot of numerical aperture versus refractive index for plastic and glass optical fiber is presented in figures 8.25, 8.26.

8.10 Evanescent wave

During the present investigations the main experimental feature which is required to be explained is the variations of output power with the refractive index of the liquid medium in which the sensing length is immersed. The main features of the experimental work are as follows.

Optical fibers both plastic and glass are used with some portion of the fiber prepared in such a way that the cladding is removed from a portion of 1cm to 2cm. This portion which is called the sensing length is immersed in guiding liquid of various concentrations and refractive index.

When the experiment is performed with a plastic (or) glass optical fiber and different operating wavelengths and sensing length, it is found that power output decreases with increase in refractive index of the medium. The power loss increases with refractive index of the medium. In order to explain this phenomenon an insight of mechanism by which the power is transmitted in optical fibers is needed. As is well known that the power transmitted takes place with the help of evanescent wave which is characterized by the
Fig. 8.21: Graph showing V-number versus power loss when 1cm/1.5cm/2cm core of plastic fiber exposed in guiding liquid of various densities of adulterated palm oil at 820nm.
Fig. 8.22: Graph showing V-number versus power loss when 1cm/1.5cm/2cm core of plastic fiber exposed in guiding liquid of various densities of adulterated palm oil at 850nm
Fig. 8.23: Graph showing V-number versus power loss when 1cm/1.5cm/2cm core of glass fiber exposed in guiding liquid of various densities of adulterated palm oil at 1300nm.
Fig. 8.24: Graph showing V-number versus power loss when 1 cm/1.5 cm/2 cm core of glass fiber exposed in guiding liquid of various densities of adulterated palm oil at 1550 nm.
Fig. 8.25: Graph showing refractive index of the guiding medium (palm oil) and numerical aperture of plastic fiber.
Fig. 8.26: Graph showing refractive index of the guiding medium (palm oil) and numerical aperture of glass fiber.
distribution of power between the core and the cladding of an optical fiber. "While in the core we have an oscillating field traversing along the length of the fiber", in cladding the field distribution is not oscillatory but represents an exponential decay. So the core – cladding distribution of power in principle can be evaluated for different modes in which the power is transmitted. It is interesting to note that certain higher order modes under certain conditions, as much as 90% of the power is transmitted through the cladding. Thus in case of an optical fiber the cladding also plays important role in transmission of power. There are methods by which core – cladding ratio (or) core cladding distribution of power to total power can be estimated from certain experimental quantities.

8.11 Power distribution between core-clad

The no. of modes that a multimode step index fiber can support is given by the expression

\[ \nu^2 = \left( \frac{2na}{\lambda} \right)^2 \left( n_1^2 - n_2^2 \right) \]

Where, \( \lambda \) is the operating wavelength
\( n_1 \) is refractive index of the core
\( n_2 \) is refractive index of the cladding
\( a \) is diameter of the fiber core

The ‘\( \nu \)’ number is also related to the no. of modes ‘M’ in a multimode fiber. The relation between these two quantities is given by

\[ M = \frac{\nu^2}{2} \]

The factor ‘2’ comes because a plane wave as two different orientation polarizations. When an optical signal is transmitted through core-cladding optical fiber system, part of the power is transmitted through the cladding in the form of evanescent wave. It has been shown that the total average fractional optical power flowing in the cladding is given by
\[ \frac{P_{clad}}{P_{total}} = \frac{4}{3} M^{-1/2} \]

\[ = \frac{2\sqrt{2}}{3} \frac{\lambda}{\pi d} \left( n_1^2 - n_2^2 \right)^{1/2} \]

and \( P_{total} = P_{core} + P_{clad} \)

Where, \( P_{total} \) = the total power in the fiber

\( P_{core} \) = power in the core

\( P_{clad} \) = power in the clad

We can calculate the ratio \( \frac{P_{clad}}{P_{total}} \) using the above expression since all the quantities are known. For example in the core of plastic and glass fibers the ratio works out to be

a) For plastic optical fiber at an operating wavelength of 820nm the fraction of the power is varying from 0.00649 to 0.0228 as refractive index of the guiding liquid vary from 1.425 to 1.448.

b) For plastic optical fiber at an operating wavelength of 850nm the fraction of the power is varying from 0.00673 to 0.02370 as refractive index of the guiding liquid vary from 1.425 to 1.448.

c) For glass optical fiber at an operating wavelength of 1300nm the fraction of the power is varying from 0.02447 to 0.03485 as refractive index of the guiding liquid vary from 1.425 to 1.448.

d) For glass optical fiber at an operating wavelength of 1550nm the fraction of the power is varying from 0.02917 to 0.04156 as refractive index of the guiding liquid vary from 1.425 to 1.448.

However the point of interest is the core-cladding distribution of power in the sensing region i.e., where cladding is removed from the central portion of
the fiber, which is immersed in the liquid and the liquid acts as cladding for the sensing length. As refractive index of medium changes from 1.425 to 1.448 the relative distribution of power in the core-cladding region goes on changing. The variation is graphically presented in fig. 8.27, 8.28, 8.29, 8.30.

The fractional power calculation in the cladding for the fibers used, different operating wavelengths and sensing lengths are presented in the form of graphs of the observed fractional power in the cladding versus power loss in fig. 8.31, 8.32, 8.33, 8.34. It can be seen that the variation of the fractional powers in the cladding, \( \frac{P_{clad}}{P_{total}} \), refractive index of the medium corresponds to power loss. i.e., as refractive index of liquid medium increases the fractional power in the cladding also increases and relates to power loss. This gives us an indication of the fractional power in the cladding is the primary source of power loss. This is expected because of the general considerations. When the liquid acts as cladding for sensing length the power in the cladding is not transmitted but dissipate in the liquid medium itself. It can also be seen that for lower values of refractive index of a liquid medium the power in cladding will be less and correspondingly the total experimental power loss observed is also small.
Fig. 8.27: Graph showing refractive index versus $P_{clad}/P_{total}$ at 820nm of plastic fiber when core is exposed to adulterated palm oil.

Refractive index of guiding medium:
- 1.425
- 1.428
- 1.431
- 1.434
- 1.437
- 1.440
- 1.443
- 1.446

$P_{clad}/P_{total}$ values:
- 0.0074
- 0.0084
- 0.0104
- 0.0114
- 0.0124
- 0.0134
- 0.0154

820nm
Fig. 8.28: Graph showing refractive index versus Pclad/Ptotal at 850nm of plastic fiber when core is exposed to adulterated palm oil.
Fig. 8.29: Graph showing refractive index versus Pclad/Ptotal at 1300nm of plastic fiber when core is exposed to adulterated palm oil
Fig. 8.30: Graph showing refractive index versus Pclad/Ptotal at 1550nm of plastic fiber when core is exposed to adulterated palm oil
Fig. 8.31: Graph showing $\frac{P_{\text{clad}}}{P_{\text{total}}}$ versus power loss at 820nm when 1cm/1.5cm/2cm core of plastic fiber exposed in guiding liquid of various densities of adulterated palm oil
Fig. 8.32: Graph showing Pclad/Ptotal versus power loss at 820nm when 1cm/1.5cm/2cm core of plastic fiber exposed in guiding liquid of various densities of adulterated palm oil.
Fig. 8.33: Graph showing $P_{\text{clad}}/P_{\text{total}}$ versus power loss at 1300nm when 1cm/1.5cm/2cm core of glass fiber exposed in guiding liquid of various densities of adulterated palm oil.
Fig. 8.34: Graph showing Pclad/Ptotal versus power loss at 1550nm when 1cm/1.5cm/2cm core of glass fiber exposed in guiding liquid of various densities of adulterated palm oil.
The above result establishes a fact that power is transmitted from the first part of the fiber to the third part of the fiber through the core and the guiding liquid which forms the sensing length. The power present in the liquid medium is dissipated. Therefore the above result establish the mechanism for the variation of power loss with refractive index of the medium.