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Passive Fiber Optic Evanescent Wave Sensor for the Measurement of Refractive Index at Various Temperatures using a Tunable Light Source

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***Abstract**: The study of refractive index of liquids over a range of 10oC to 60oC shows very interesting results to design and develop a highly sensitive passive fiber optic sensor based on a U-shaped glass probe. The depth of penetration of light that escaping from the core of the fiber into the cladding plays a crucial role in the development of a highly sensitive fiber optic evanescent wave sensor. The depth of penetration of an optical fiber striped off its cladding is directly related to the wavelength of the light, the index of refraction of the surrounding medium, the angle of incidence of light, the bending radius and thickness of the U-shaped probe. In the design of the sensor a U-shaped glass probe is used to replace the core of the fiber in the region of sensing, the diameter of which is same as that of the cores of a pair of insensitive fibers which in-turn connected to a tunable light source and an optical detector. The sensor is highly reliable, robust and easy to configure using multimode PCS fibers and the source operating at the wavelengths of 630nm, 660nm, 820nm and 850nm.*

***Keywords**: Depth of penetration, Fiber optic evanescent wave sensor, insensitive fibers, Optical detector, Tunable light source, U-shaped glass probe.*

I. INTRODUCTION

The evanescent wave penetrates into the analyte ranges from ten to several hundred nanometers during course of its interaction of an analyte with the escaping field of light that traverses through an optical fiber. Because of its short range depth of penetration of the evanescent wave, the measurements are not affected by bulk solution [1]. The fiber optic evanescent wave sensors consisting of a plastic clad silica core optical fibers are now a days have been used in a wide range of fields such as chemical, biochemical, food technology, fragrant, beverages, life sciences and environmental research, etc [2-3]. The sensitivity offered by the evanescent wave sensors are very high comparing to the other kinds of sensors based on various designs [4]. For the enhancement of the sensitivity of the fiber optic evanescent wave sensor various geometries have been considered to measure innumerable environmental parameters [5]. Majority of the schemes of the fiber optic evanescent wave sensors have concentrated on the optimization of the shape of the sensing element and the end of the probe in the region of sensing. Many researchers have used the techniques of surface plasma resonance (SPR) to enhance further the specificity and sensitivity of the evanescent wave sensors [6]. The intensity of the evanescent field on the unclad fiber surface is very important in developing the enhanced sensitive evanescent field sensor [7]. The sensitivity of the sensor depends upon increase in the amount of light escaping into the analyte and decreases in the number of meridional rays propagate within the fiber. The loss of evanescent wave is determined by number of total reflections and their depth of penetration. The transmission spectrum of fiber is sensitive to various measurands such as temperature, strain [8], external refractive index [9-10] and bend radius [11-14]. Corresponding to each measurand the attenuation band shows a different sensitivity offering for the construction of multi-parameter sensing systems [15]. It is possible to extract a wide range of quantitative information, moment of a single cell and composition using the measurement of evanescent wave. For the study of rate of chemical reaction, thin films of organic metals, curing of complex material, liquid solid interfaces, gas and liquid detection and biological applications, etc, using probe or sensing element in the construction of an evanescent wave sensor have been reported [16-18]. The evanescent wave penetrates into the surrounding and accordingly the power in the core decreases exponentially when the surrounding medium refractive index is close to less than 5% of the core and fiber cladding is 5units of wavelength in thickness [19].

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II. EXPERIMENTAL DETAILS

The experimental Procedure was initiated by properly selecting the various components that forms part of the experimental arrangement. For the effective measurement of the refractive index of liquids a tunable light source was selected along with other necessary components listed as under.

1. A tunable light source (LASER diode) operating at the wavelengths of 630nm, 660nm, 820nm and 850nm.
2. A benchmark light detector operating at the wavelengths of 630nm, 660nm, 820nm and 850nm.
3. A pair of plastic clad silica (PCS) fibers of 200/230μm core and cladding diameters respectively.
4. A borosilicate glass rod bent in the form of a U-shape, the thickness of which is equal to diameter of the core of a pair of multimode PCS fibers used in the experiment.

5. A two burette system to measure the volumes of liquid mixtures in required ratios.
6. An automatic digital refractometer of modal number RX-7000i (Atago make).
7. An electric kettle heater to heat the chemical mixture to above the room temperature.
8. An ice bath arrangement to reduce the temperature of chemical mixture below room temperature down to 10ºC.

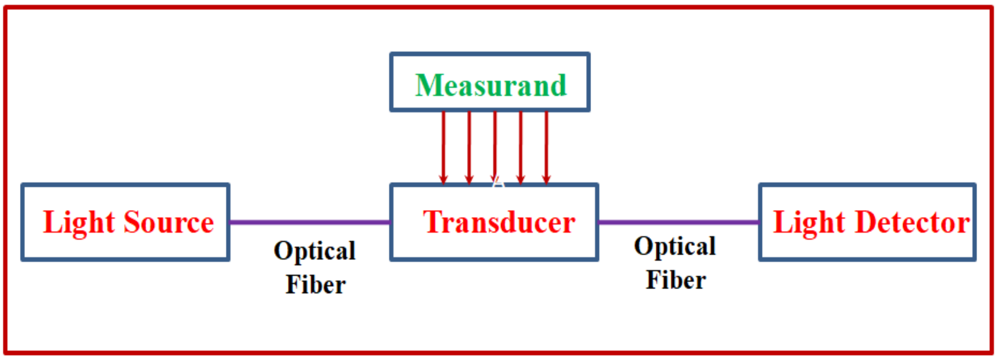
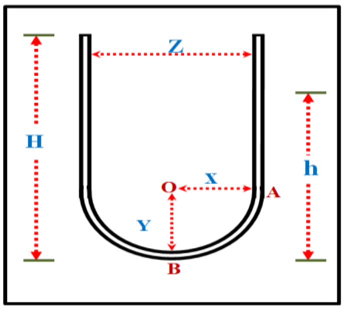


Figure.1: Block diagram of fiber optic sensor system.

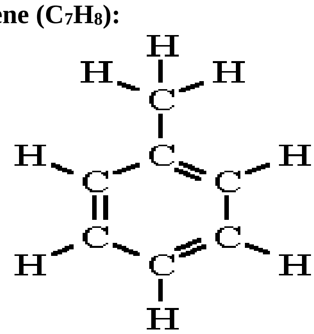


Thickness of rod:	0.5mm
Total height of the glass rod(H):	40mm
Depth of the glass rod immersed in liquid(h):	30mm
Width between two prongs(Z):	5mm
Radius of the Curvature(X):	2.5mm
Depth of the Curvature(Y):	2.5mm

Figure.2: Geometrical parameters of U-shaped borosilicate glass probe.

Chemical parameter of Toluene (C_7H_8):

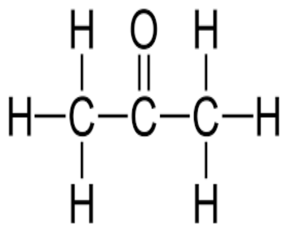
Structure:



CAS Number:	108-88-3
Molar Mass (g/mole):	92.141
Refractive index (n):	1.4967 at 20ºC
Density(ρ) (kg/m^3):	0.8697×10^3 at 20ºC
Color:	Colorless
Boiling Point (ºC):	110.6ºC

Chemical parameter of Acetone (C_3H_6O):

Structure:



CAS Number:	67-64-1
Molar Mass (g/mole):	58.080
Refractive index (n):	1.3588 at 20ºC
Density(ρ) (kg/m^3):	0.7845×10^3 at 20ºC
Color:	Colorless
Boiling Point (ºC):	56.08ºC

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The assembly of the experimental arrangement consist of a uniform U-shaped glass rod connected between a tunable light source operating at the wavelengths of 630nm, 660nm, 820nm and 850nm and a benchmark light detector by using a pair of PCS fibers. A two burette system fixed at certain height using stands, the mixture of Toluene and Acetone is taken in different proportions making the total volume equal to 20ml and each is preserved in a separate glass bottle closed with air tight lids. Launching light into the sensor by tuning the source to the operating wavelength of 630nm, the U-shaped glass rod is immersed in first mixture of Toluene and Acetone with the ratio of 20ml + 0ml and the power output is noted from the detector at room temperature.

The procedure is repeated by rising the temperature of the mixture to 60°C in steps of 5°C each using electric kettle heater and the observations are recorded. Similar method is used when the temperature of the mixture decreased from room temperature to 10°C in steps of 5°C each using a cooling setup consisting of an ice bath and a thermometer.
The above steps of experimental method was followed using the other mixtures of the combination of Toluene and Acetone and the results obtained are recorded for all the different temperatures i.e. at room temperature, above room temperature up to 60°C and below room temperature up to 10°C and all the observations are noted [table-1].

Table.1: Mole fraction and concentration of Acetone in Toluene + Acetone chemical mixture and Output power at various temperatures for the operating wavelength of the source 630nm.

S. No.	Mole fraction of Acetone	Concentration of Acetone	Output Power(dBm) at various temperatures										
			10°C	15°C	20°C	25°C	30°C	35°C	40°C	45°C	50°C	55°C	60°C
1	0.0000	0%	-44.90	-44.53	-44.17	-43.73	-43.33	-42.97	-42.57	-42.27	-41.77	-41.47	-41.10
2	0.0718	10%	-43.00	-42.60	-42.33	-41.93	-41.80	-41.53	-41.30	-41.00	-40.73	-40.33	-40.00
3	0.1483	20%	-41.57	-41.33	-41.07	-40.73	-40.43	-40.10	-39.83	-39.50	-39.20	-38.90	-38.57
4	0.2299	30%	-40.53	-40.20	-39.93	-39.57	-39.30	-39.00	-38.73	-38.43	-38.00	-37.83	-37.53
5	0.3171	40%	-39.17	-38.90	-38.57	-38.30	-37.97	-37.77	-37.47	-37.13	-36.83	-36.50	-36.27
6	0.4106	50%	-37.97	-37.77	-37.47	-37.13	-36.83	-36.50	-36.27	-35.90	-35.60	-35.30	-35.07
7	0.5110	60%	-36.70	-36.40	-36.13	-35.83	-35.53	-35.23	-35.00	-34.63	-34.33	-34.00	-33.70
8	0.6191	70%	-35.07	-34.70	-34.40	-34.10	-33.80	-33.47	-33.20	-32.90	-32.60	-32.33	-32.00
9	0.7359	80%	-33.53	-33.20	-32.90	-32.60	-32.33	-32.00	-31.73	-31.40	-31.10	-30.80	-30.50
10	0.8624	90%	-31.83	-31.53	-31.20	-30.93	-30.57	-30.27	-30.07	-29.80	-29.60	-29.40	-29.13
11	1.0000	100%	-30.50	-30.27	-29.97	-29.70	-29.57	-29.30	-29.03	-28.77	-28.43	-28.17	-27.80

Next, the source is tuned to the operating wavelength of 660nm and using all the mixtures one by one at the temperatures ranging from 10°C to 60°C using ice bath and electric kettle heater, the output powers corresponding to each mixture is noted from the detector and were recorded [table-2].

Table.2: Mole fraction and concentration of Acetone in Toluene + Acetone chemical mixture and Output power at various temperatures for the operating wavelength of the source 660nm.

S. No.	Mole fraction of Acetone	Concentration of Acetone	Output Power(dBm) at various temperatures										
			10°C	15°C	20°C	25°C	30°C	35°C	40°C	45°C	50°C	55°C	60°C
1	0.0000	0%	-45.23	-44.87	-44.47	-44.07	-43.63	-43.27	-42.87	-42.57	-42.03	-41.80	-41.40
2	0.0718	10%	-43.30	-42.90	-42.60	-42.20	-42.10	-41.87	-41.57	-41.30	-41.07	-40.60	-40.30
3	0.1483	20%	-41.90	-41.60	-41.33	-41.07	-40.70	-40.40	-40.13	-39.83	-39.53	-39.20	-38.90
4	0.2299	30%	-40.83	-40.50	-40.23	-39.90	-39.63	-39.30	-39.03	-38.73	-38.30	-38.10	-37.83

5	0.3171	40%	-39.50	-39.20	-38.90	-38.60	-38.27	-38.03	-37.77	-37.43	-37.13	-36.80	-36.57
6	0.4106	50%	-38.27	-38.03	-37.77	-37.43	-37.13	-36.80	-36.57	-36.20	-35.93	-35.60	-35.37
7	0.5110	60%	-37.00	-36.70	-36.43	-36.13	-35.83	-35.53	-35.30	-34.93	-34.63	-34.33	-34.03
8	0.6191	70%	-35.37	-35.00	-34.70	-34.40	-34.10	-33.73	-33.50	-33.23	-32.93	-32.63	-32.30
9	0.7359	80%	-33.80	-33.50	-33.23	-32.93	-32.63	-32.30	-32.03	-31.73	-31.40	-31.10	-30.80
10	0.8624	90%	-32.10	-31.83	-31.50	-31.20	-30.87	-30.57	-30.30	-30.10	-29.90	-29.67	-29.43
11	1.0000	100%	-30.80	-30.57	-30.23	-30.00	-29.83	-29.57	-29.30	-29.00	-28.73	-28.40	-28.10

The above procedure is followed by tuning the light source to the operating wavelengths of 820nm and 850nm separately and results are tabulated [table 3-4].

Table.3: Mole fraction and concentration of Acetone in Toluene + Acetone chemical mixture and Output power at various temperatures for the operating wavelength of the source 820nm.

S. No.	Mole fraction of Acetone	Concentration of Acetone	Output Power(dBm) at various temperatures										
			10ºC	15ºC	20ºC	25ºC	30ºC	35ºC	40ºC	45ºC	50ºC	55ºC	60ºC
1	0.0000	0%	-46.87	-46.47	-46.17	-45.73	-45.30	-44.93	-44.57	-44.27	-43.77	-43.43	-43.07
2	0.0718	10%	-45.00	-44.60	-44.47	-43.93	-43.80	-43.50	-43.27	-43.00	-42.77	-42.30	-42.00
3	0.1483	20%	-43.57	-43.30	-43.00	-42.77	-42.40	-42.10	-41.77	-41.50	-41.23	-40.90	-40.73
4	0.2299	30%	-42.47	-42.20	-41.93	-41.57	-41.30	-41.00	-40.73	-40.43	-40.03	-39.80	-39.50
5	0.3171	40%	-41.20	-40.90	-40.73	-40.30	-40.00	-39.70	-39.43	-39.13	-38.87	-38.50	-38.27
6	0.4106	50%	-40.00	-39.70	-39.43	-39.13	-38.87	-38.50	-38.27	-37.83	-37.60	-37.30	-37.03
7	0.5110	60%	-38.70	-38.40	-38.13	-37.80	-37.50	-37.23	-37.00	-36.57	-36.33	-36.00	-35.70
8	0.6191	70%	-37.03	-36.70	-36.40	-36.10	-35.80	-35.40	-35.17	-34.90	-34.60	-34.33	-34.00
9	0.7359	80%	-35.50	-35.17	-34.90	-34.60	-34.33	-34.00	-33.70	-33.40	-33.10	-32.80	-32.50
10	0.8624	90%	-33.83	-33.50	-33.17	-32.93	-32.53	-32.23	-32.00	-31.70	-31.47	-31.20	-30.97
11	1.0000	100%	-32.50	-32.23	-31.93	-31.57	-31.40	-31.13	-30.87	-30.53	-30.33	-29.97	-29.70

Table.4: Mole fraction and concentration of Acetone in Toluene + Acetone chemical mixture and Output power at various temperatures for the operating wavelength of the source 850nm.

S. No.	Mole fraction of Acetone	Concentration of Acetone	Output Power(dBm) at various temperatures										
			10ºC	15ºC	20ºC	25ºC	30ºC	35ºC	40ºC	45ºC	50ºC	55ºC	60ºC
1	0.0000	0%	-47.20	-46.87	-46.43	-46.00	-45.63	-45.23	-44.87	-44.53	-44.03	-43.77	-43.43
2	0.0718	10%	-45.27	-44.90	-44.60	-44.23	-44.10	-43.83	-43.57	-43.27	-43.07	-42.60	-42.33
3	0.1483	20%	-43.87	-43.60	-43.30	-43.07	-42.70	-42.37	-42.10	-41.80	-41.50	-41.20	-40.90
4	0.2299	30%	-42.80	-42.47	-42.23	-41.87	-41.60	-41.30	-41.03	-40.73	-40.30	-40.10	-39.83
5	0.3171	40%	-41.47	-41.20	-40.90	-40.60	-40.23	-40.00	-39.77	-39.43	-39.17	-38.80	-38.50
6	0.4106	50%	-40.23	-40.00	-39.77	-39.43	-39.17	-38.80	-38.50	-38.17	-37.90	-37.60	-37.37

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7	0.5110	60%	-39.00	-38.70	-38.43	-38.13	-37.83	-37.53	-37.30	-36.93	-36.63	-36.30	-36.00
8	0.6191	70%	-37.37	-37.00	-36.70	-36.40	-36.10	-35.70	-35.50	-35.30	-34.90	-34.53	-34.30
9	0.7359	80%	-35.77	-35.50	-35.30	-34.90	-34.53	-34.30	-34.03	-33.70	-33.40	-33.10	-32.80
10	0.8624	90%	-34.10	-33.80	-33.50	-33.23	-32.87	-32.53	-32.30	-32.00	-31.77	-31.50	-31.30
11	1.0000	100%	-32.80	-32.53	-32.23	-31.87	-31.73	-31.43	-31.17	-30.90	-30.60	-30.27	-30.03

By using an Automatic Digital Refractometer of modal number RX-7000i (Atago make), the refractive index of each mixture was determined at temperature ranging from 10ºC to 60ºC in steps of 5ºC and experimental results are tabulated [table-5].

Table.5: Mole fraction and concentration of Acetone in Toluene + Acetone chemical mixture and Refractive indices of mixtures at various temperatures.

S. No.	Mole fraction of Acetone	Concentration of Acetone	Refractive Index at various temperatures										
			10ºC	15ºC	20ºC	25ºC	30ºC	35ºC	40ºC	45ºC	50ºC	55ºC	60ºC
1	0.0000	0%	1.50915	1.50591	1.50171	1.49770	1.49325	1.48974	1.48582	1.48293	1.47795	1.47509	1.47102
2	0.0718	10%	1.48997	1.48614	1.48305	1.48005	1.47922	1.47588	1.47298	1.47002	1.46720	1.46398	1.46004
3	0.1483	20%	1.47612	1.47308	1.47041	1.46720	1.46402	1.46112	1.45831	1.45523	1.45241	1.44905	1.44600
4	0.2299	30%	1.46528	1.46211	1.45923	1.45602	1.45323	1.45008	1.44734	1.44441	1.44128	1.43808	1.43548
5	0.3171	40%	1.45201	1.44905	1.44600	1.44307	1.44009	1.43714	1.43422	1.43119	1.42818	1.42504	1.42221
6	0.4106	50%	1.44009	1.43714	1.43422	1.43119	1.42818	1.42504	1.42221	1.41912	1.41600	1.41305	1.41008
7	0.5110	60%	1.42712	1.42428	1.42118	1.41821	1.41529	1.41221	1.40930	1.40618	1.40311	1.40054	1.39752
8	0.6191	70%	1.41008	1.40709	1.40411	1.40108	1.39814	1.39464	1.39218	1.39001	1.38627	1.38326	1.38018
9	0.7359	80%	1.39522	1.39218	1.39001	1.38627	1.38326	1.38018	1.37731	1.37424	1.37131	1.36854	1.36541
10	0.8624	90%	1.37824	1.37519	1.37224	1.36935	1.36605	1.36279	1.36011	1.35719	1.35424	1.35115	1.34827
11	1.0000	100%	1.36541	1.36279	1.35937	1.35635	1.35348	1.35010	1.34718	1.34425	1.34154	1.33829	1.33533

III. RESULT AND DISCUSSION

The temperature study of refractive index of liquids paves the way for the understanding of macroscopic behavior of the liquids at various temperatures. The variation of refractive index and hence the concentration shows a direct relationship with the power reaching the detector at the room temperature. As the refractive index of mixture increases, the output power decreases, which is an inverse power relationship with the concentration of the chemical mixture. The similar behavior is observed at each temperature of liquid taken in the steps of 5oC for each of chemical mixture from 10oC to 60oC when the source is fixed at the operating wavelength of 630nm and results are shown in figures [fig.3-5].

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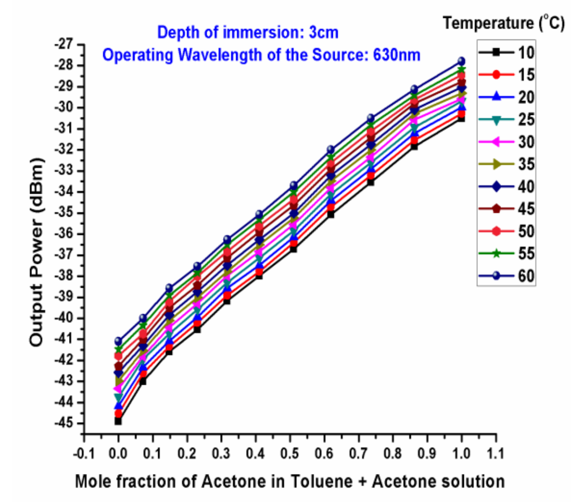

Fig.3: Relation between Mole fraction of Acetone in Toluene + Acetone solution and Output power for operating wavelength of the source 630nm.

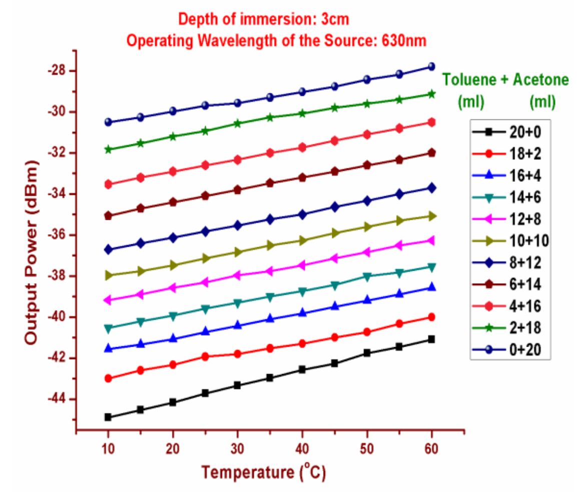

Fig.4: Relation between Temperature and Output power of Toluene + Acetone solution for operating wavelength of the source 630nm.

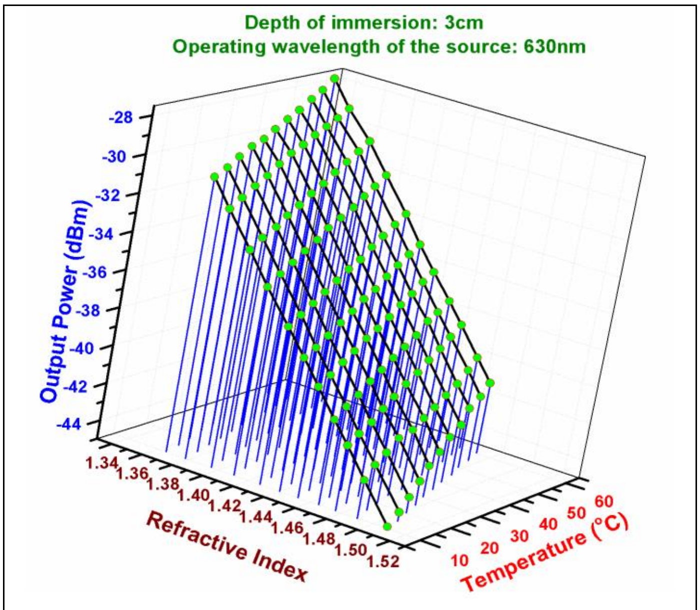

Fig.5: Relation between Refractive index, Output Power and Temperature of Toluene + Acetone solution for operating wavelength of the source 630nm.

The experiment is performed with the source operating wavelength at 660nm and the results are depicted graphically [fig.6-8].

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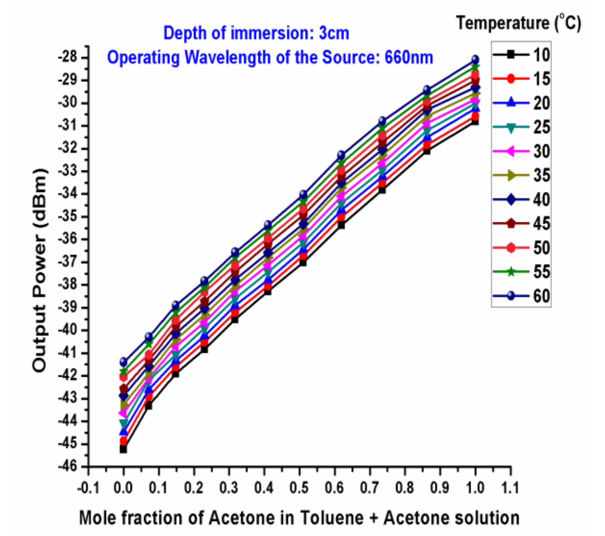

Fig.6: Relation between Mole fraction of Acetone in Toluene + Acetone solution and Output power for operating wavelength of the source 660nm.

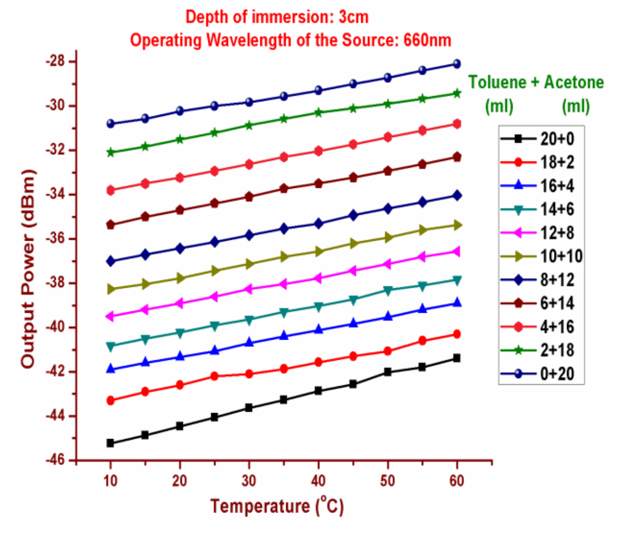

Fig.7: Relation between Temperature and Output power of Toluene + Acetone solution for operating wavelength of the source 660nm.

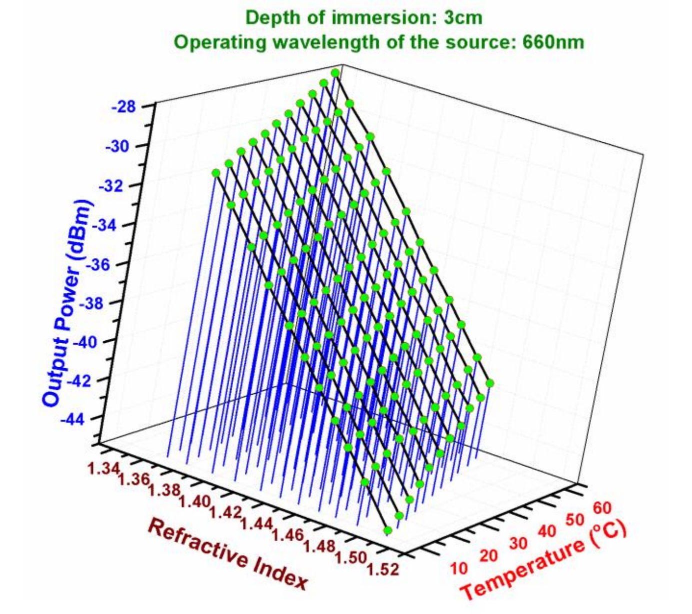

Fig.8: Relation between Refractive index, Output Power and Temperature of Toluene + Acetone solution for operating wavelength of the source 660nm.

The variation in output powers at different temperature for various chemical mixtures shows that the output powers are reduces at the wavelength of 660nm comparing with the 630nm. To ascertain the variation of output power with respect to wavelength two other wavelength (820nm, 850nm) also been considered and used in experimentation and results are obtained and the relationships between them are shown graphically [fig. 9-14].

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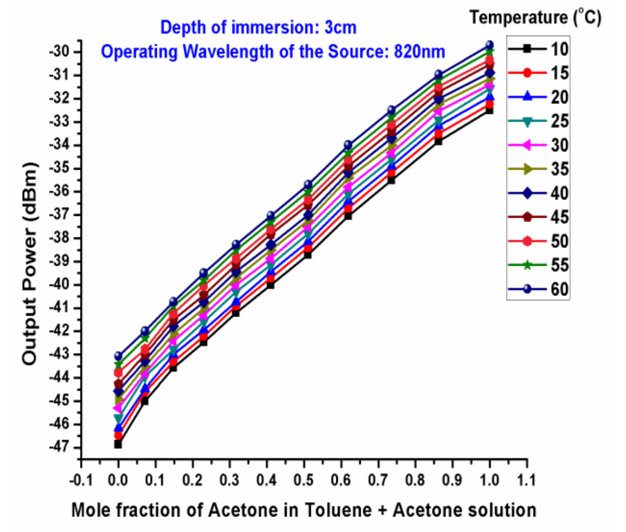

Fig.9: Relation between Mole fraction of Acetone in Toluene + Acetone solution and Output power for operating wavelength of the source 820nm.

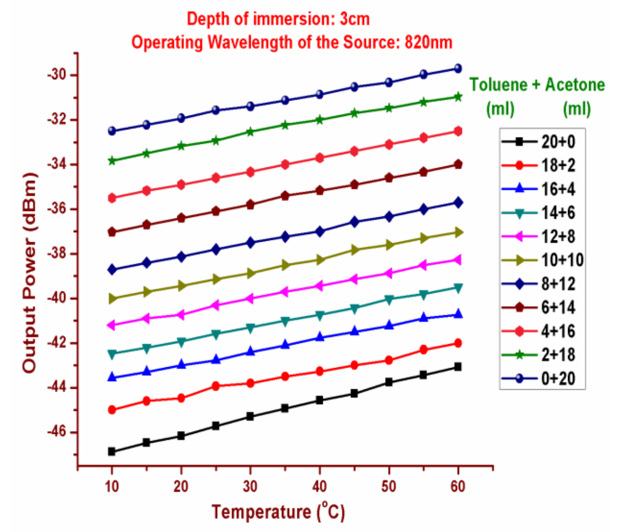

Fig.10: Relation between Temperature and Output power of Toluene + Acetone solution for operating wavelength of the source 820nm.

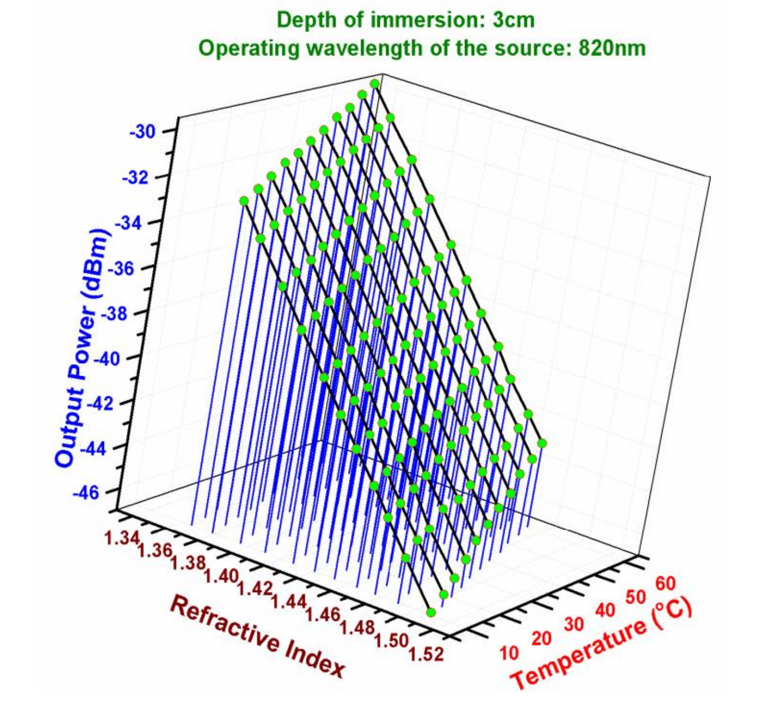

Fig.11: Relation between Refractive index, Output Power and Temperature of Toluene + Acetone solution for operating wavelength of the source 820nm.

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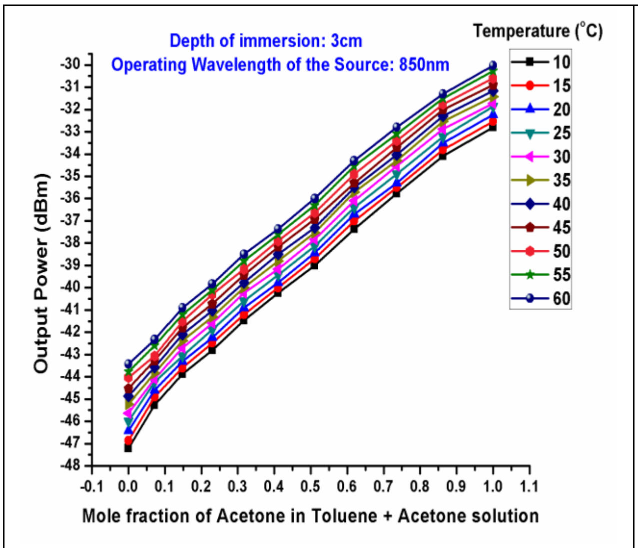

Fig.12: Relation between Mole fraction of Acetone in Toluene + Acetone solution and Output power for operating wavelength of the source 850nm.

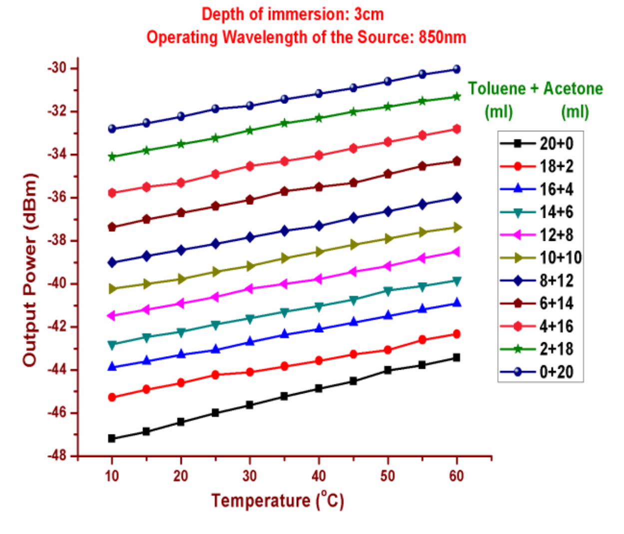

Fig.13: Relation between Temperature and Output power of Toluene + Acetone solution for operating wavelength of the source 850nm.

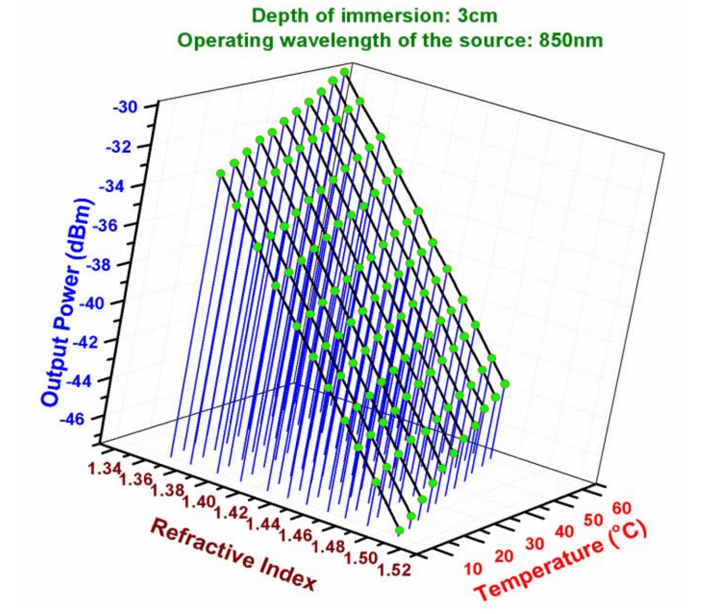

Fig.14: Relation between Refractive index, Output Power and Temperature of Toluene + Acetone solution for operating wavelength of the source 850nm.

From the above graphs (figs. 9-14) it is confirmed that the output powers are reduced when the wavelength is increased. In addition to the study of power transmission in the sensor at different temperatures and at different operating wavelengths, the mole fractions and the concentrations of all the mixture at different temperature have been experimentally studied and the results are represented graphically [fig.15-17].

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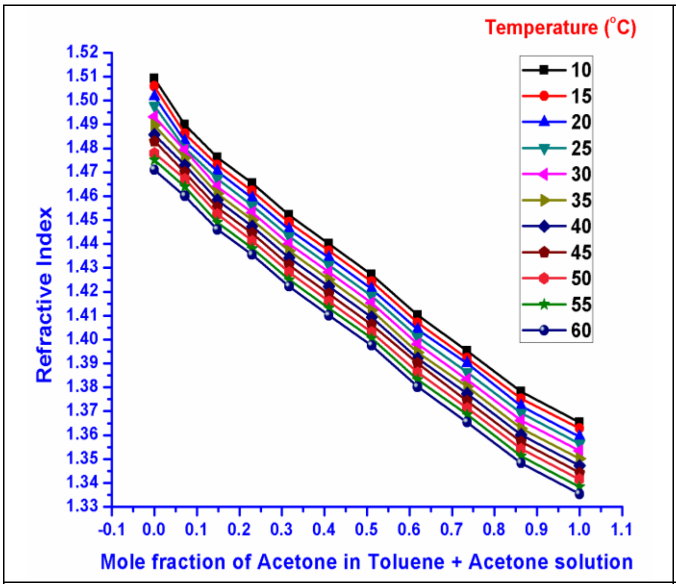

Fig.15: Relation between Mole fraction of Acetone in Toluene + Acetone solution and Refraction index.

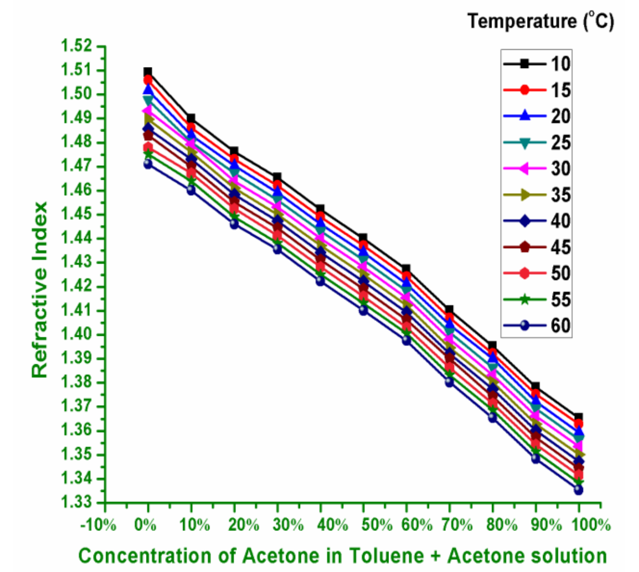

Fig.16: Relation between Concentration of Acetone in Toluene + Acetone solution and Refraction index.

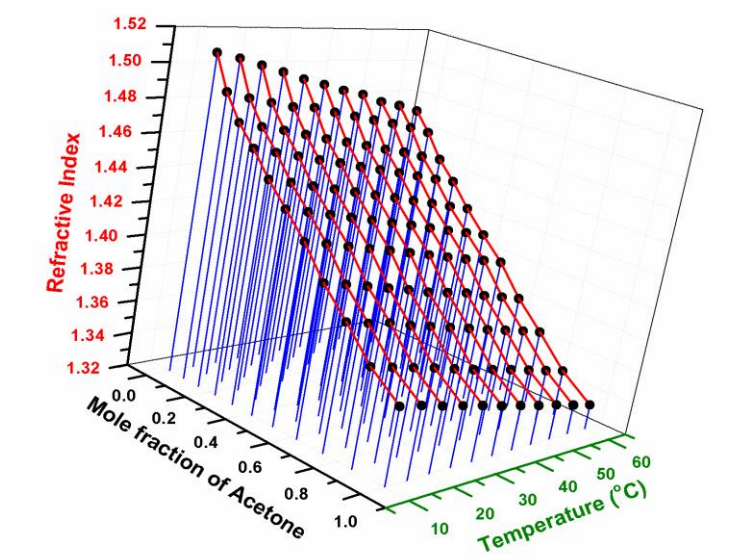

Fig.17: Relation between Mole fraction of Acetone in Toluene + Acetone solution, Refraction index and Temperature.

IV. CONCLUSION

The study of operational nature of the passive fiber optic evanescent wave sensor for the measurement of refractive index at various temperatures using a tunable light source operating at the wavelengths of 630nm, 660nm, 820nm and 850nm has been taken up between temperature ranges from 10ºC to 60ºC. The experimental results revels that the output power decreases with increasing the refractive index hence concentration of chemical mixture forms as a liquid cladding at any fixed value of temperature. The output power also decreases when the operating wavelength of the tunable light source increase which is also in agreement with the literature values. The decrease of refractive index of chemical mixture at high temperatures has nominal affect above room temperature i.e., from 30ºC to 60ºC and also the increase in refractive index of chemical mixture at low temperature also has a little affect when temperature reduces from 30ºC to 10ºC below room temperature.

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