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Multifunctional Extrinsic Fiber Optic Sensor to Measure Various Parameters of Liquids at the Operating Wavelength of 660nm Employing a U-Shaped Glass Rod as a Sensing Element

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Abstract*: Fiber Optic sensor technology has become more popular since early 1970's during which the mechanism of losses from optical fibers was exploited to construct a new class of fiber optic sensors and systems. A novel fiber optic sensor has been developed by connecting a U-shaped glass element of specific dimensions between a light source of 660nm wavelength and an optical power detector by using a couple of PCS optical fibers of 200/230μm diameters of core and cladding respectively. The sensor can be employed to measure several parameters such as Refractive Index, Density, Viscosity, Ultrasonic Velocity, Molar Volume, Molar Refraction, Dielectric Constant, Acoustic Impendence, Adiabatic Compressibility, Viscous Relaxation Time, Intermolecular Free Length, Absorption Coefficient, Gibb's Free Energy, Free Volume, Internal Pressure and their excess parameters of Toluene and tert-Butanol mixtures at 30℃ temperature and at the operating wavelength of 660nm.

Keywords* : Absorption Coefficient, Acoustic Impendence, Adiabatic Compressibility, Density, Excess Parameters, Free Volume, Gibb's Free Energy, Intermolecular Free Length, Internal Pressure, Refractive Index, Ultrasonic Velocity, U-Shaped Glass Element, Viscosity, Viscous Relaxation Time.

I. INTRODUCTION

Since early 1970's there is lot of revolutionary inventions taken place in the field of fiber optic sensors due to their advantages over the electrical sensor systems. The fiber optic sensors have been developed based on the observation of sensitivity of the transmission characteristics of optical fiber on certain internal and certain external perturbations [1-6]. Internal perturbations: presence of micro-structural variations in the glass matrix, impurities, hydroxyl ion, evolution of hydrogen from the fabrication of cable, bubbles, voids, change in the refractive index, etc.

External perturbations: pressure, temperature, strain, micro-bend and macro-bend, etc.

Optical fiber telecommunication soon saw R and D activity across the world which led to the emergence of the field of fiber optic sensors [7]. The fiber optic sensing technology offers substantial benefits as compare to conventional electrical sensors. 1. The signal transmission is immune to electromagnetic interference (EMI) and radio frequency interference (RFI). 2. The sensors are safe in explosive and hazardous environment. 3. The raw material sand is abundantly available across the world. 4. The systems are reliable and secure with no risk of spark and fire. 5. Low volume and weight makes them to construct miniatured systems. 6. Without perturbation of transmitted signal they can be used as point sensors to measure the parameters form inaccessible regions. 7. They are resistance to ionizing and nuclear radiations. 8. They efforts remote sensing by locating the source and detector far away from the sensor head. 9. The system can be used in the distributed sensing to sense various parameters along length of the fiber. These advantages make them to attract intensive R and D activity to develop a new class of sensors based on optical fibers [8]. This has led to the development of a variety of fiber optic sensors for the measurement of various field and physical parameters like electric field, magnetic field, acoustic field, acceleration, displacement, rotation, electric current, liquid pH and liquid refractive index and so on. Based on the measurand to be measure various designs and configurations have been developed by various authors and reported in the literature [9-12]. The intermolecular interaction between the molecules of components has been reported [13], which finds applications in several chemical and industrial processes. With respect to variation in concentration of liquids and temperatures, the ultrasonic velocity and acoustic parameters like adiabatic compressibility, free length, relaxation time, acoustic impedance, etc., with their excess values provide valuable information about the molecular environment [14-18].

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II. EXPERIMENTAL PART

The experimental arrangement consist of a U-shaped glass rod connected between a light source of 660nm and a bench mark power detector using a couple of PCS optical fibers one at the input end and other at the output end. Chemical mixtures of Toluene and tert-Butanol at different ratios making total volume equivalent to 20ml have been prepared using a two burette system and taken each mixture into a separate air tight glass bottle.

Determination of Refractive Index and Output Power: The Refractive index of each mixture was determined using Automatic Digital Refractometer of model no RX-7000i (Atago, Japan) at 30℃ temperature and using sodium vapour lamp with an accuracy of 10^{-5}. By fixing the depth of immersion as 1cm, the U-shaped glass rod has been immersed into each liquid one by one and the light is launched from the source, then the light reaching the detector was recorded. This process is repeated by fixing the depth of immersion of U-shaped glass rod into the liquid as 2cm and 3cm, Thus by fixing the operating wavelength of the source at 660nm, the variation of output powers for different depths of immersions have been noted and recorded.

Determination of Ultrasonic Velocity (U): An ultrasonic interferometer of model no M-84, supplied by M/S Mittal enterprises, New Delhi, was used to measure the ultrasonic velocity at 30 ℃ with an accuracy of $\pm 0.1 m.s^{-1}$ and at operating frequency of 4MHz. For the constancy of temperature, the water is circulated through the outer jacket of the double walled measuring cell of an electrically operated digital constant temperature controller of model no SSI-03 Spl, supplied by M/S Mittal enterprises, New Delhi. Operating in the temperature range of –10℃ to 85℃ with an accuracy of ±0.1℃ was used.

Determination of Density (ρ): Using a 25ml specific gravity bottle the densities of all the mixtures were measured by relative measurement method with an accuracy of $\pm 0.1 kg.m^{-3}$. The experimental mixture in the specific gravity bottle was immersed in the temperature control water bath and an electronic digital balance (model no. SHIMADZU AX-200, Kyoto, Japan) was used to measure the weight of the sample with an accuracy of ±0.1mg.

$$\rho_2 = (w_2/w_1)\rho_1$$

Where: ρ_1 & ρ_2 are densities of distilled water and chemical solutions

w_1 & w_2 are weights of distilled water and chemical solutions

Determination of Viscosity (η): The viscosity measurement was done using an Oswald viscometer with an accuracy of $\pm 0.001 N.s.m^{-2}$. A digital racer stop watch with an accuracy of ±0.1sec was used to determine the time of flow of the liquid.

$$\eta_2 = \eta_1(t_2/t_1)(\rho_2/\rho_1)$$

Where: η_1 & η_2 are viscosities of distilled water and chemical solution

ρ_1 & ρ_2 are densities of distilled water and chemical solution

w_1 & w_2 are weights of distilled water and chemical solution

III. THEORITICAL ASPECTS OF OTHER CHEMICAL PARAMETERS

From the end results of experimental values and the observations, it is concluded that various kinds of other parameters also can be derived and relationships between one and another can be analyzed. Some of the important chemical parameters that are strongly related to the experimental results are listed as follows

1. Mole Fraction $(X_a) = \frac{V_1(M_1/\rho_1)}{V_1(M_1/\rho_1)+V_2(M_2/\rho_2)}$
2. Molar Volume $(V_m) = \frac{M_1X_1+M_2X_2}{\rho_{solution}}$
3. Molar Refraction $(R_m) = \left[\frac{n^2-1}{n^2+2}\right] V_m$
4. Dielectric Constant $(\varepsilon) = n^2$
5. Acoustic Impendence (Z) = U.ρ
6. Adiabatic Compressibility $(\beta) = \frac{1}{(U^2\rho)}$
7. Viscous Relaxation Time $(\tau) = \frac{4}{3}(\beta\eta)$
8. Intermolecular Free Length $(L_f) = K_T.\beta^{1/2}$
9. Absorption Coefficient $(\alpha/f^2) = \frac{8}{3}\left[\frac{\pi^2\eta}{\rho U^2}\right]$
10. Gibb's Free Energy $(\Delta G) = K_B.T.\ln[K_B T.\tau/h]$
11. Free Volume $(V_f) = \left[\frac{M_{eff}.U}{K\eta}\right]^{3/2}$
12. Internal Pressure (Π_i) = b.R.T $\left[\frac{K.\eta}{U}\right]^{1/2}\left[\frac{\rho^{2/3}}{M_{eff}^{7/6}}\right]$

Where: $M_{eff} = \sum M_i X_i$

M_1, M_2: Molecular weights of pure chemicals

ρ_1, ρ_2: Densities of pure chemicals

V_1, V_2: Volumes of pure chemicals

X_1, X_2: Mole fractions of pure chemicals in solution

n: Refractive Index of solution

U: Ultrasonic velocity of solution at 4MHz frequency

ρ: Density of solution

η: Viscosity of solution

K_T: Temperature dependent constant (Jacobson's constant)

K_B: Boltzmann's constant

h: Plank's constant

K: Temperature and nature of liquid independent constant

b: Cubic packing (for liquids 2)

R: Universal gas constant

IV. RESULT AND DISCUSSION

The influence of the photo catalyst concentration (0.5 - 2 gL^{-1}) on the photo catalyticdegradation of Vitamin B12 drug was investigated at an initial Vitamin B12 drug concentration of 10ppm, lightintensity (1.4 mW/cm2, flow rate of O2 (5 mL. min^{-1}) and buffer concentration of thesuspension pH 6.[19]

The variations of output power is observed to be linear with respect to mole fraction of tert-Butanol in Toluene + ter-Butanol solution, for all the three depths of immersions [fig.-1].

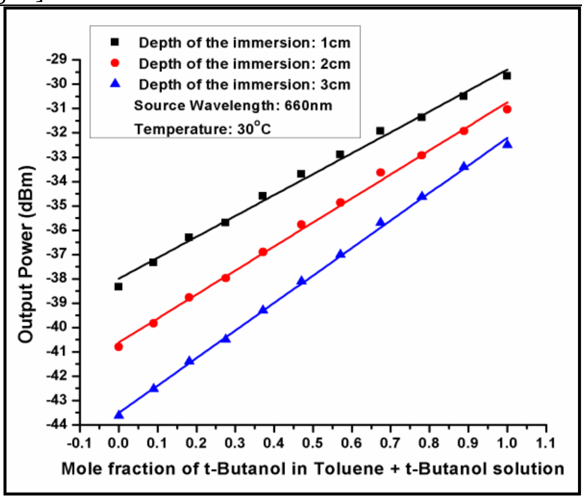

Fig.1: Relation between Mole fraction of t-Butanol in Toluene + t-Butanol solution and Output Power

The refractive indices of all the mixtures were determined using Automatic Digital Refractometer (RX-7000i) and exposing the each mixture surrounding the glass rod the power values are noted from the detector and the relationships are shown in figure[2].

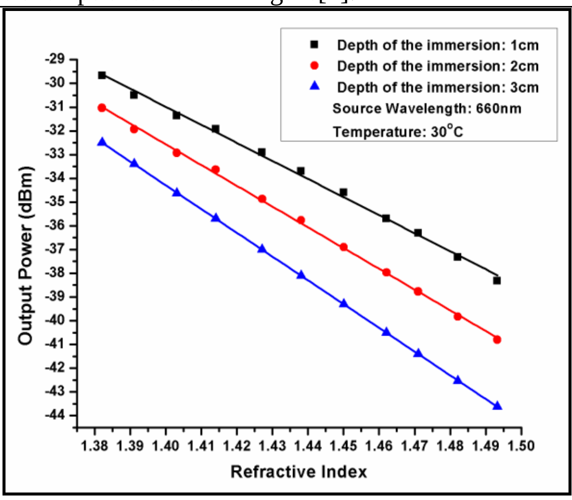

Fig.2: Relation between Refractive index and Output power of Toluene + t-butanol solution

From the measured values of densities and output power values a relationship is formed for three depths of immersions [fig.-3].

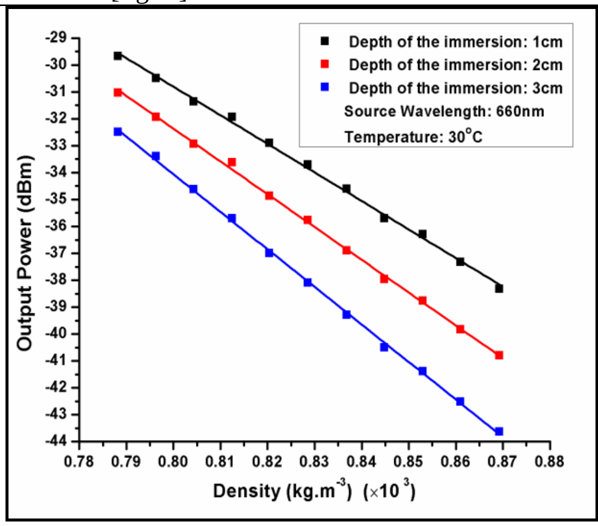

Fig.3: Relation between Density and Output power of Toluene + t-butanol solution

A linear relationship between ultrasonic velocity and the output power has been shown in figure[4].

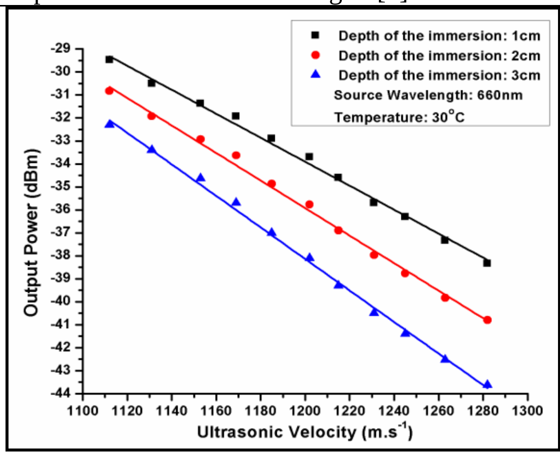

Fig.4: Relation between Ultrasonic velocity and Output power of Toluene + t-butanol solution

From the tabulated values of viscosity and output powers were related graphically in figure[5].

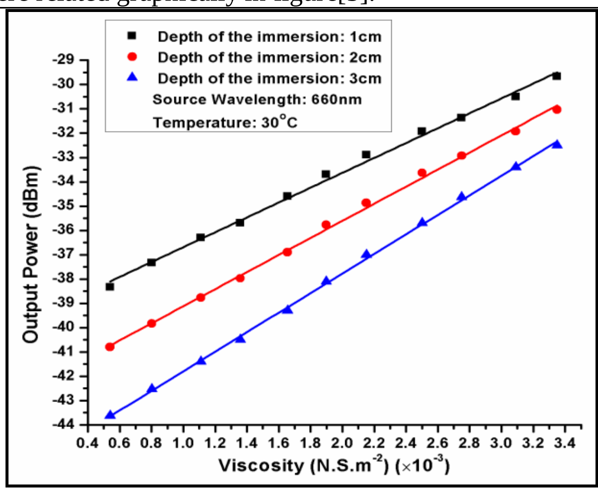

Fig.5: Relation between Viscosity and Output power of Toluene + t-butanol solution

The variation of output power with respect to molar volume, molar refraction, dielectric constant, acoustic impendence, adiabatic compressibility, viscous relaxation time, intermolecular free length, absorption coefficient, Gibb's free energy, free volume, internal pressure all parameters of the mixtures have been shown in graphs[fig.6-16].

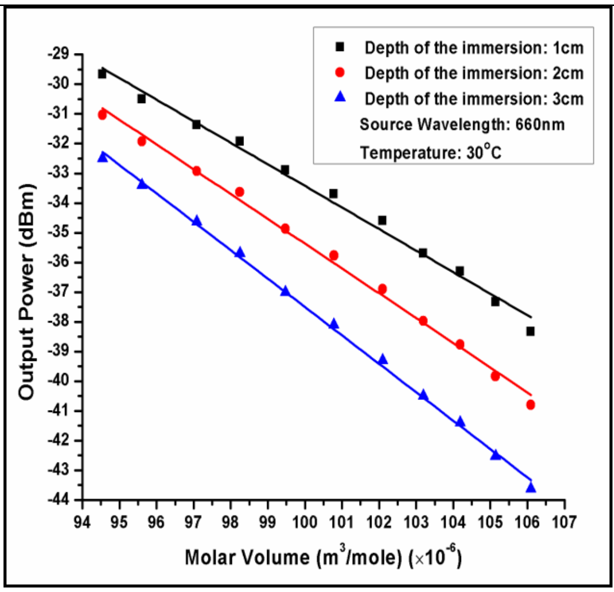

Fig.6: Relation between Molar volume and Output power of Toluene + t-butanol solution

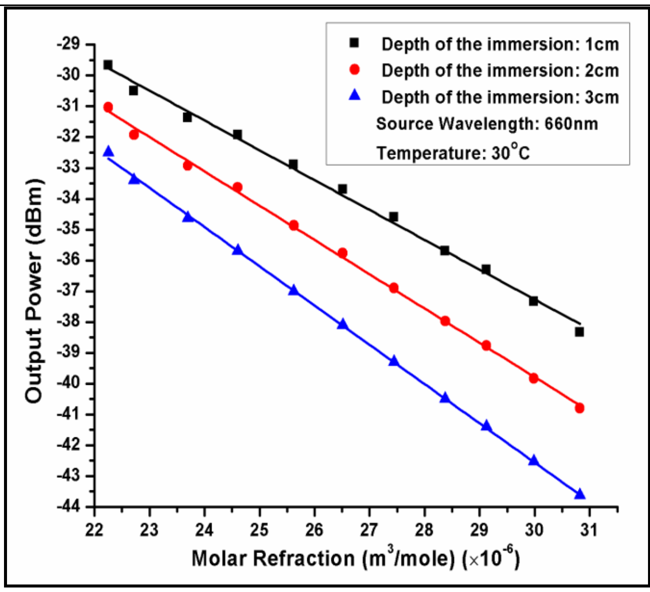

Fig.7: Relation between Molar refraction and Output power of Toluene + t-butanol solution

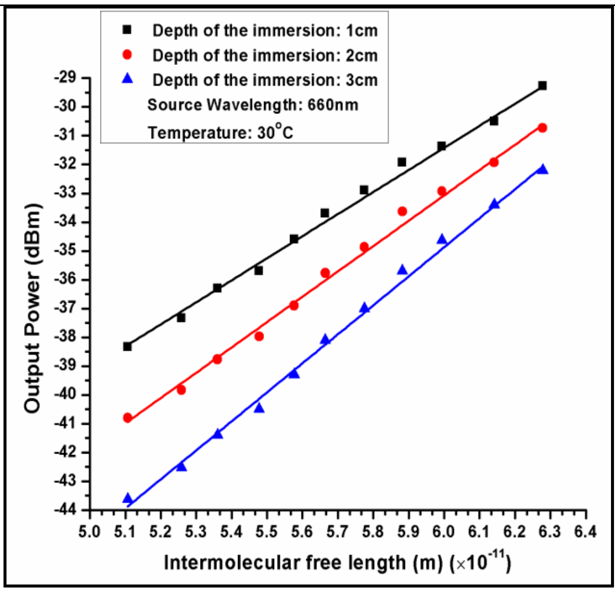

Fig.8: Relation between Intermolecular free length and Output power of Toluene + t-butanol solution

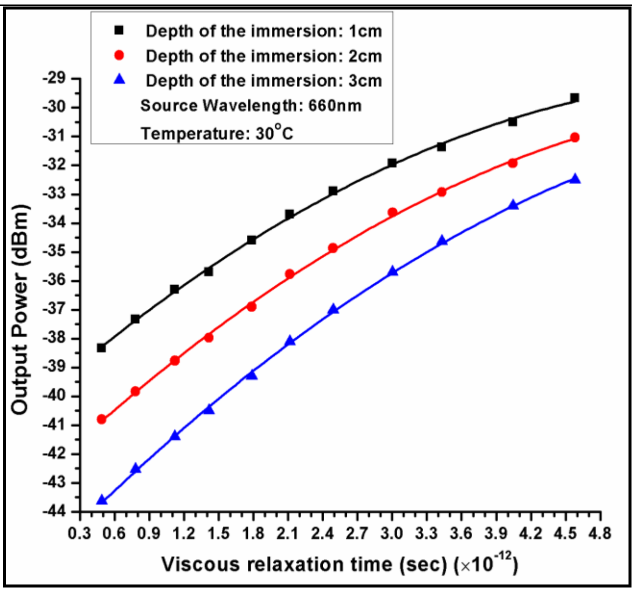

Fig.9: Relation between Viscous relaxation time and Output power of Toluene + t-butanol solution

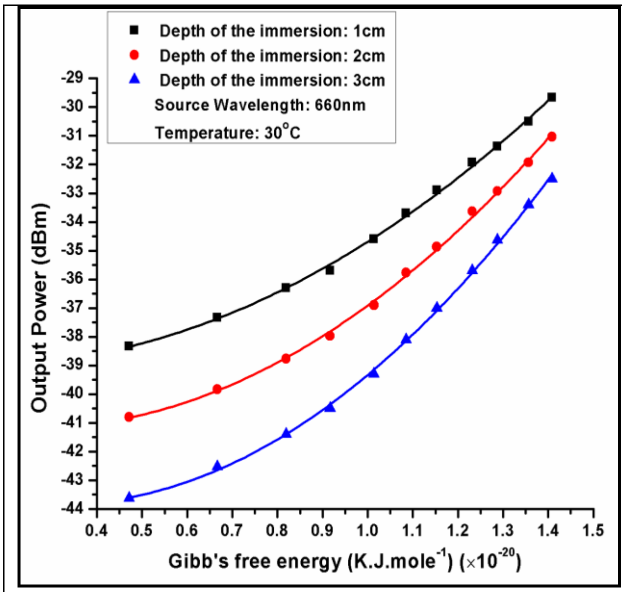

Fig.10: Relation between Gibb's free energy and Output power of Toluene + t-butanol solution

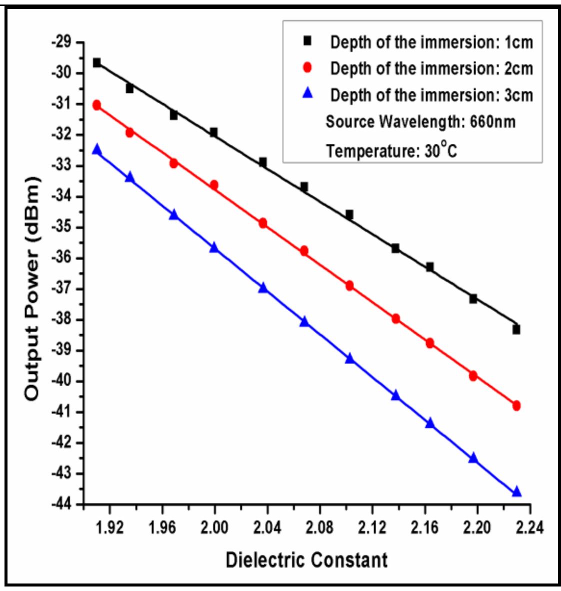

Fig.11: Relation between Dielectric constant and Output power of Toluene + t-butanol solution

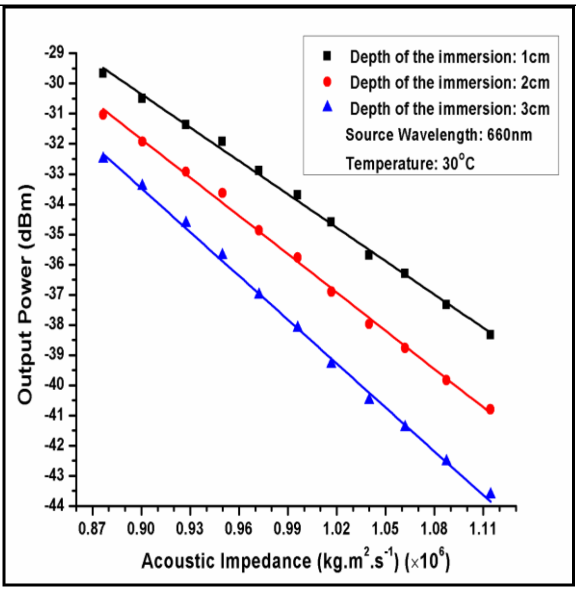

Fig.12: Relation between Acoustic impedance and Output power of Toluene + t-butanol solution

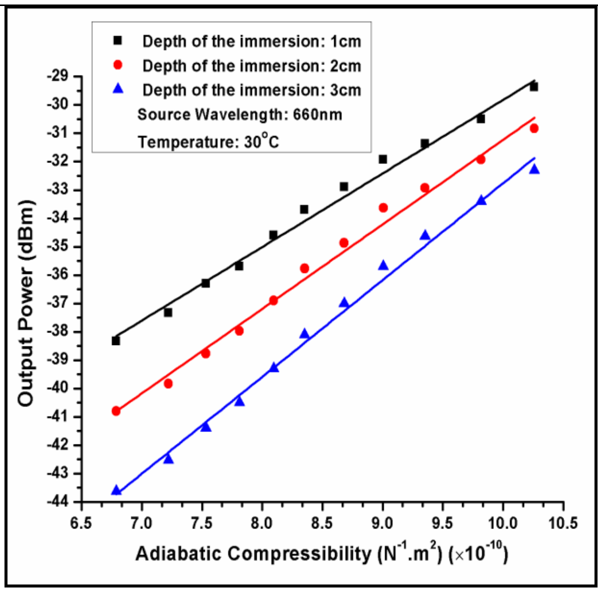

Fig.13: Relation between Adiabatic compressibility and Output power of Toluene + t-butanol solution

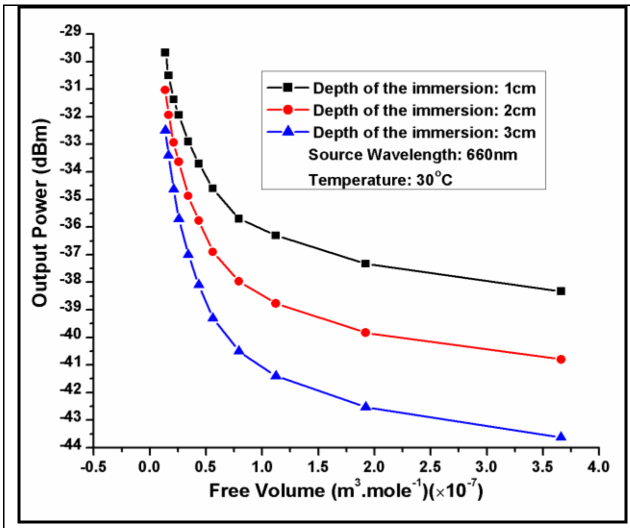

Fig.14: Relation between Free volume and Output power of Toluene + t-butanol solution

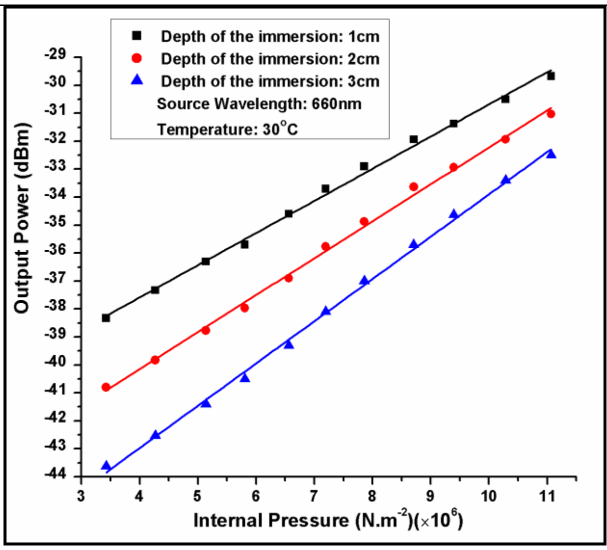

Fig.15: Relation between Internal pressure and Output power of Toluene + t-butanol solution

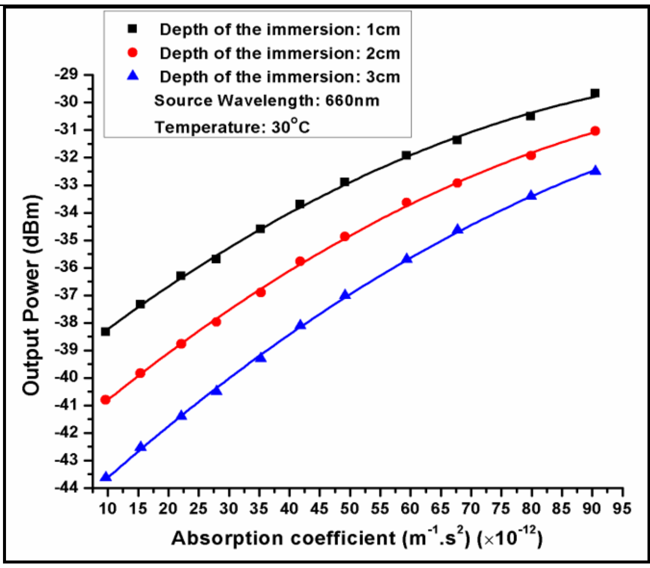

Fig.16: Relation between Absorption coefficient and Output power of Toluene + t-butanol solution

Excess parameters: The excess parameter can be defined as the difference between the properties of the chemical solution minus the sum of the product of the properties of the individual pure chemicals and mole fraction.

$$A^E = A_{solution} - \sum A_i X_i$$

Where: A^E is excess parameter

$A_{solution}$ is solution parameter

A_i is individual pure chemical parameter ; X_i is mole fraction of pure chemical.

The excess values for various properties range from absorption coefficient, acoustic impendence, adiabatic compressibility, density, dielectric constant, free volume, Gibb's free energy, intermolecular free length, internal pressure, molar refraction, molar volume, refractive index, ultrasonic velocity, viscosity, to viscous relaxation time have been calculated and results are presented graphically [fig.17-31].

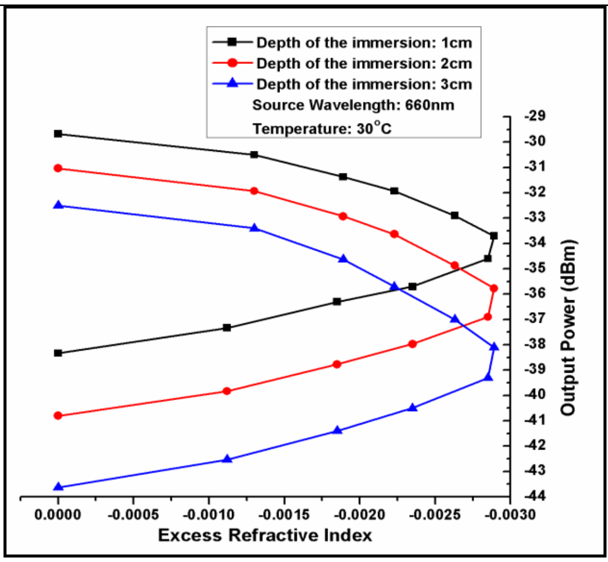

Fig.17: Relation between Excess Refractive index and Output power of Toluene + t-butanol solution

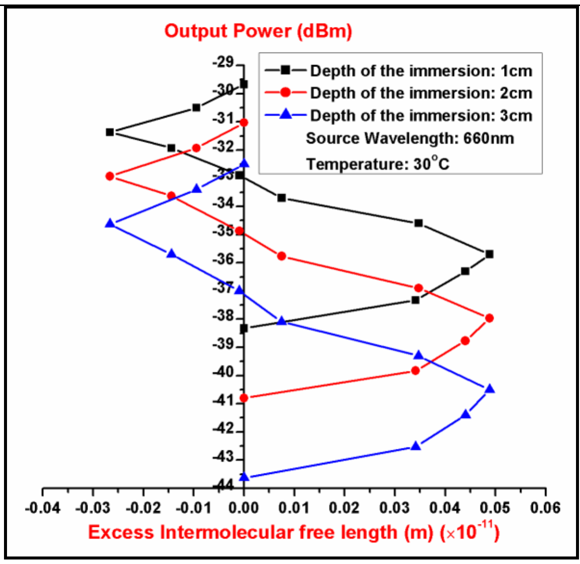

Fig.18: Relation between Excess Interemolecular free length and Output power of Toluene + t-butanol solution

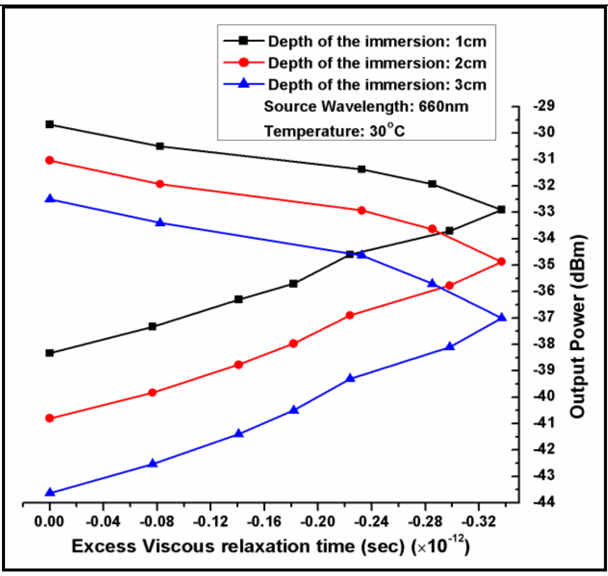

Fig.19: Relation between Excess Viscous relaxation time and Output power of Toluene + t-butanol solution

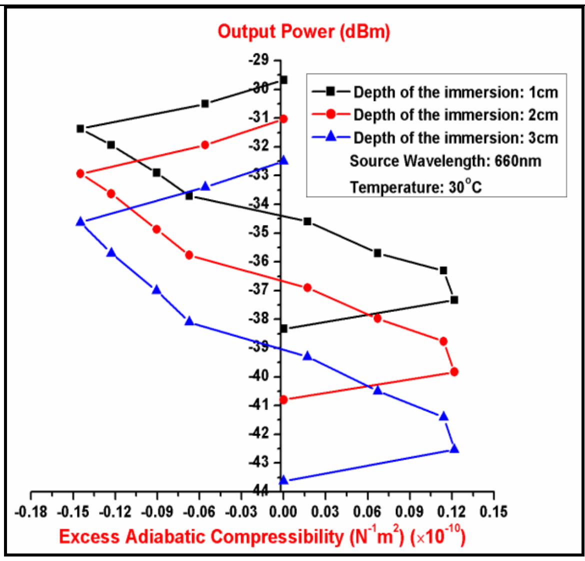

Fig.20: Relation between Excess Adiabatic compressibility and Output power of Toluene+ t-butanol solution

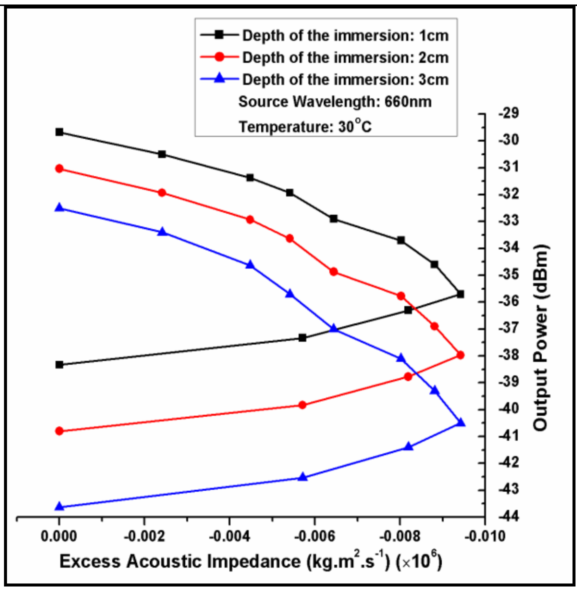

Fig.21: Relation between Excess Acoustic impedance and Output power of Toluene + t-butanol solution

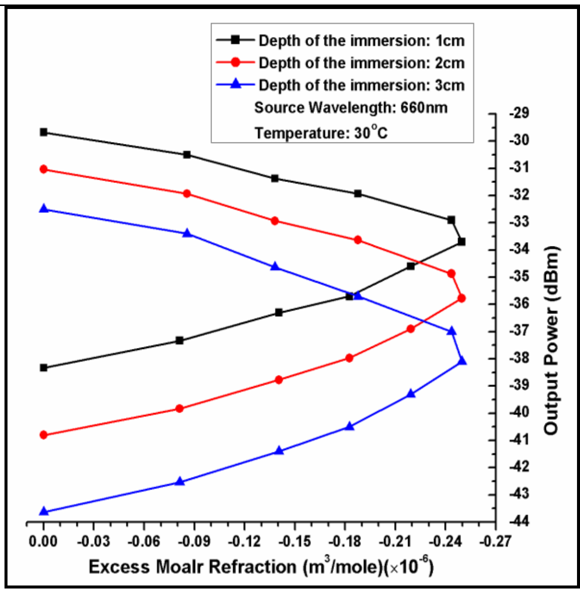

Fig.22: Relation between Excess Molar refraction and Output power of Toluene + t-butanol solution

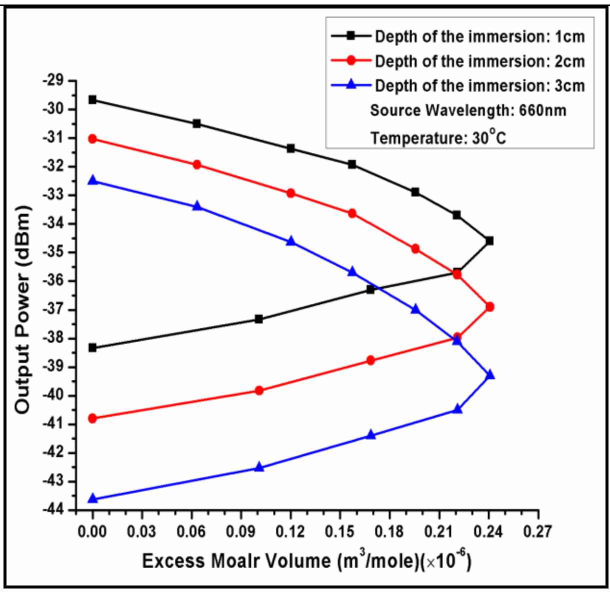

Fig.23: Relation between Excess Molar volume and Output power of Toluene + t-butanol solution

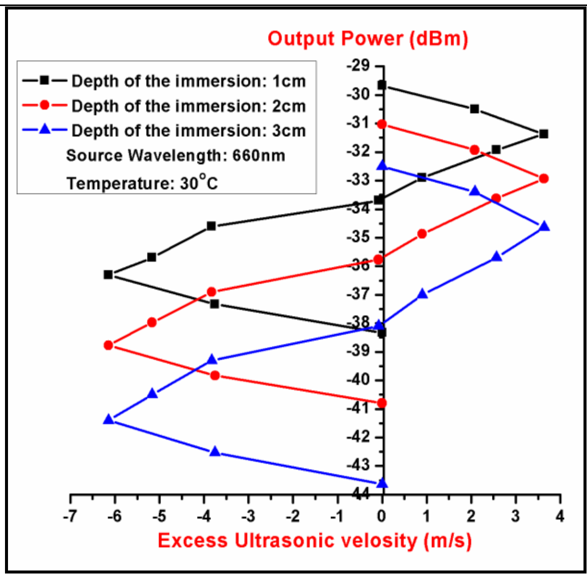

Fig.24: Relation between Excess Ultrasonic velocity and Output power of Toluene + t-butanol solution

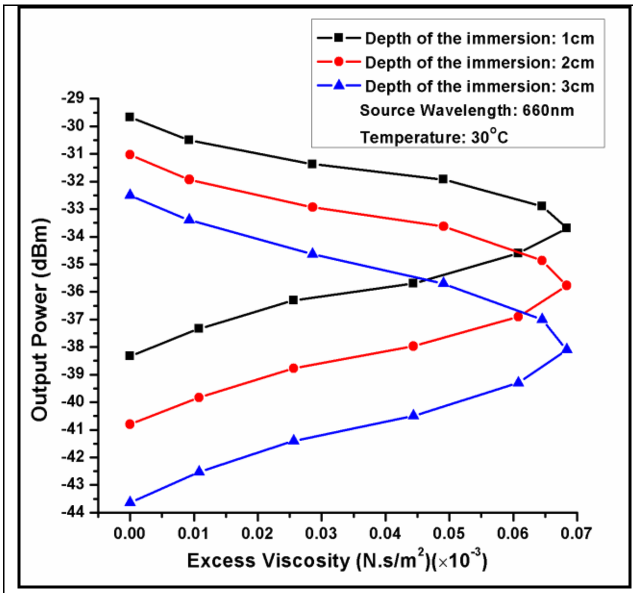

Fig.25: Relation between Excess Viscosity and Output power of Toluene + t-butanol solution

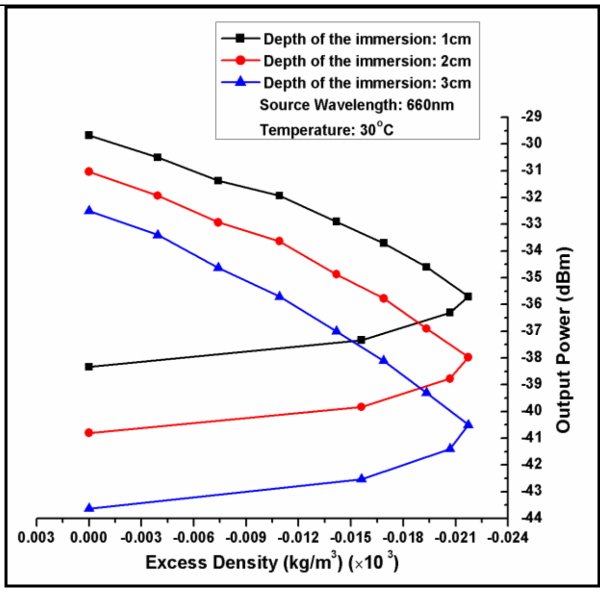

Fig.26: Relation between Excess Density and Output power of Toluene + t-butanol solution

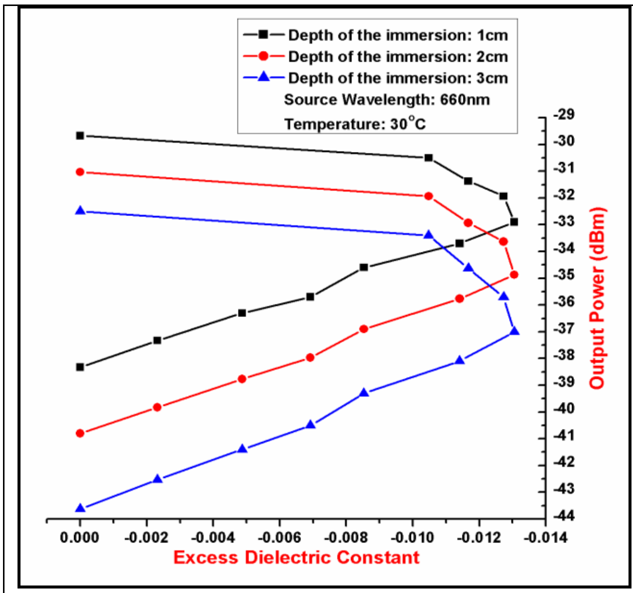

Fig.27: Relation between Excess Dielectric constant and Output power of Toluene + t-butanol solution

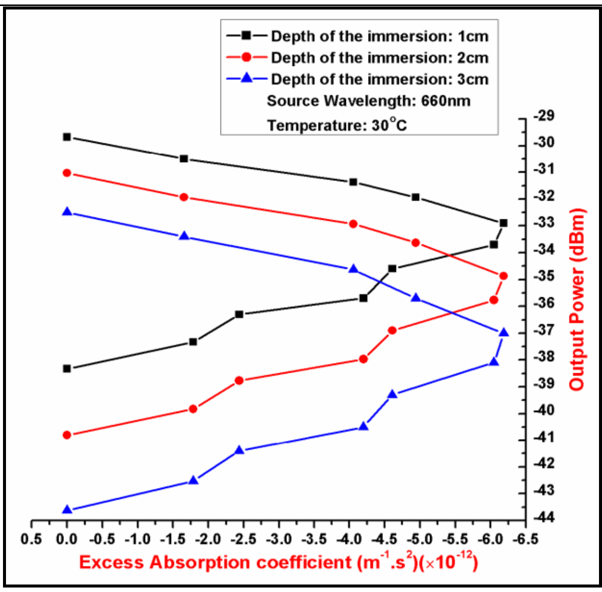

Fig.28: Relation between Excess Absorption coefficient and Output power of Toluene + t-butanol solution

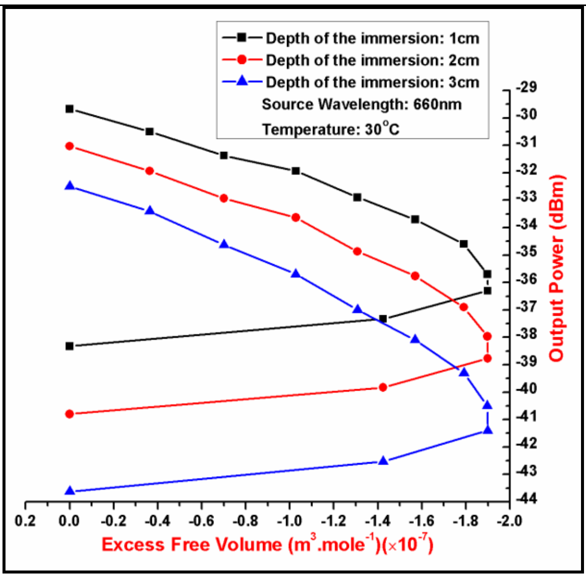

Fig.29: Relation between Excess Free volume and Output power of Toluene + t-butanol solution

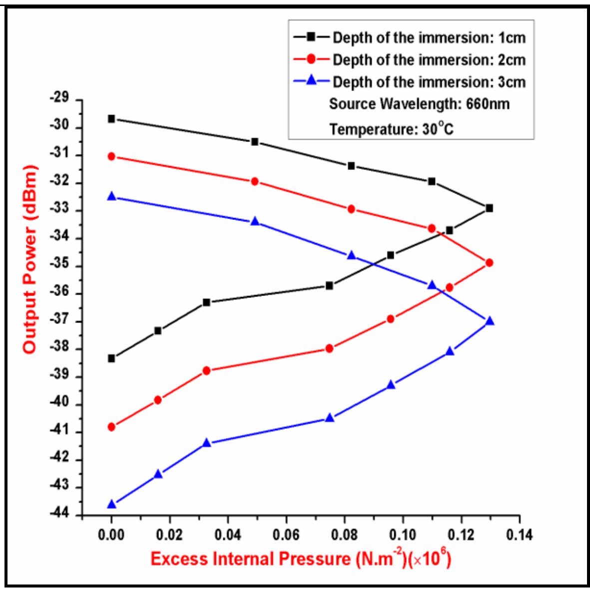

Fig.30: Relation between Excess Internal pressure and Output power of Toluene + t-butanol solution

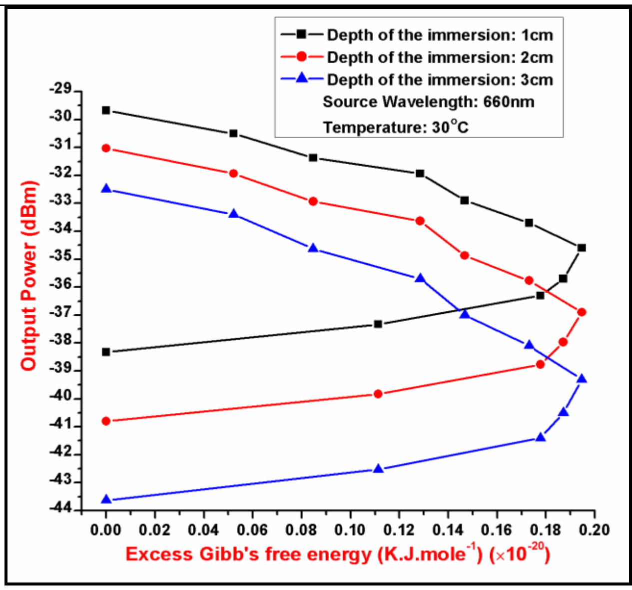

Fig.31: Relation between Excess Gibb's free energy and Output power of Toluene + t-butanol solution

Parameter Vs Excess parameters: It is interesting that how a particular parameter gives out an excess parameter, when the pure chemicals are involved in the solution. The deviation of the sum of original chemical parameters with their solution parameters have been represented in figures[32-46].

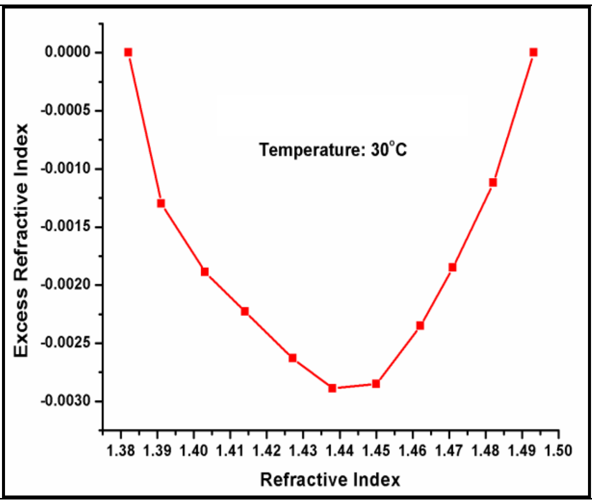

Fig.32: Relation between Refractive index and Excess refractive index of Toluene + t-butanol solution

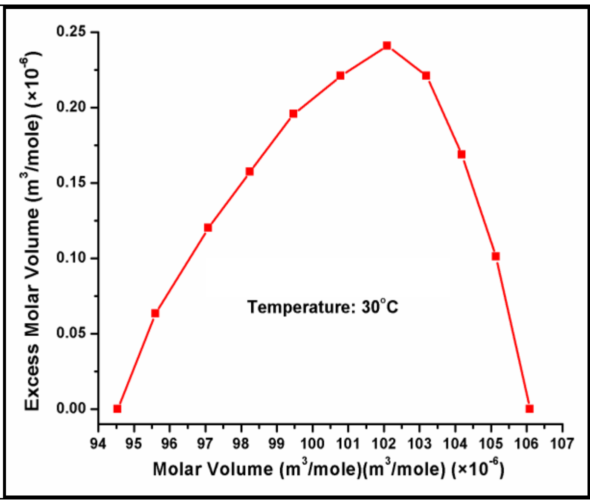

Fig.33: Relation between Molar volume and Excess Molar volume of Toluene + t-butanol solution

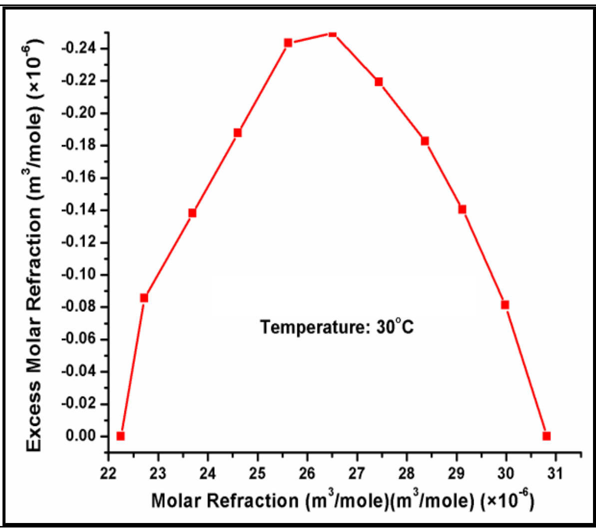

Fig.34: Relation between Molar refraction and Excess Molar refraction of Toluene + t-butanol solution

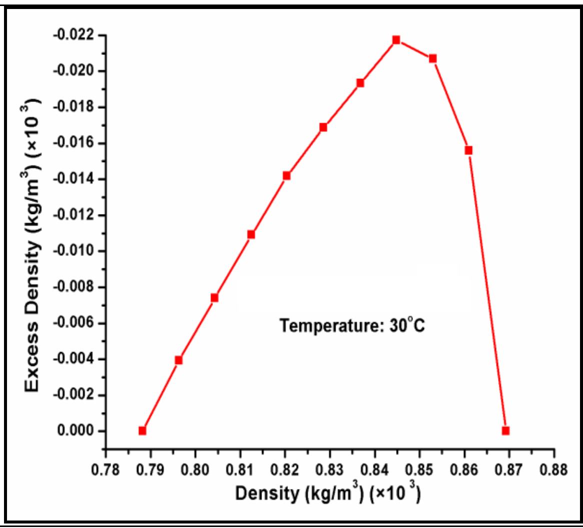

Fig.35: Relation between Density and Excess Density of Toluene + t-butanol solution

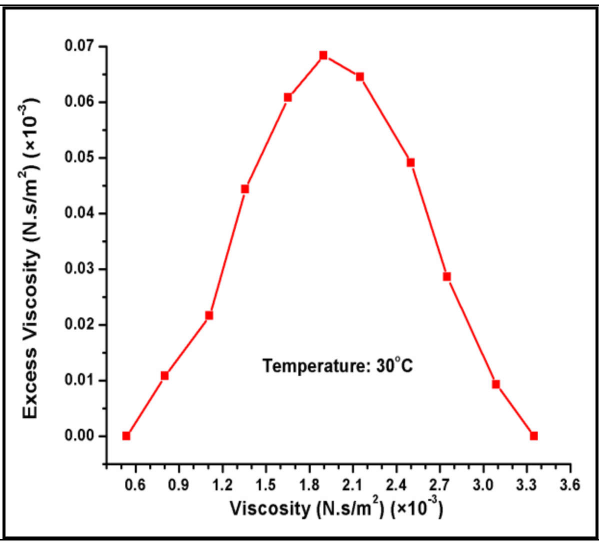

Fig.36: Relation between Viscosity and Excess Viscosity of Toluene + t-butanol solution

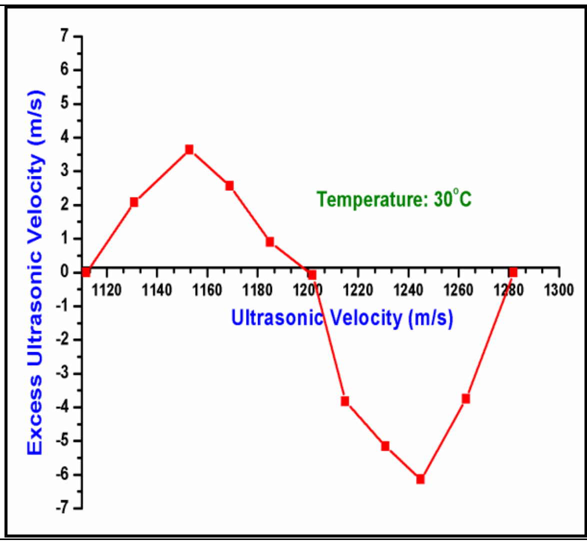

Fig.37: Relation between Ultrasonic velocity and Excess Ultrasonic velocity of Toluene + t-butanol solution

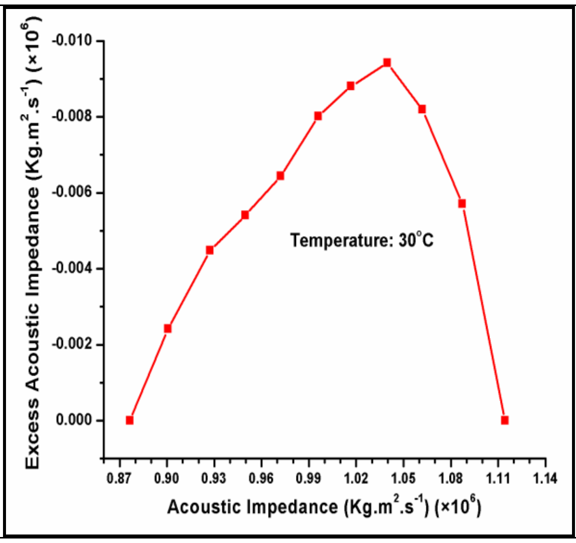

Fig.38: Relation between Acoustic impedance and Excess Acoustic impedance of Toluene + t-butanol solution

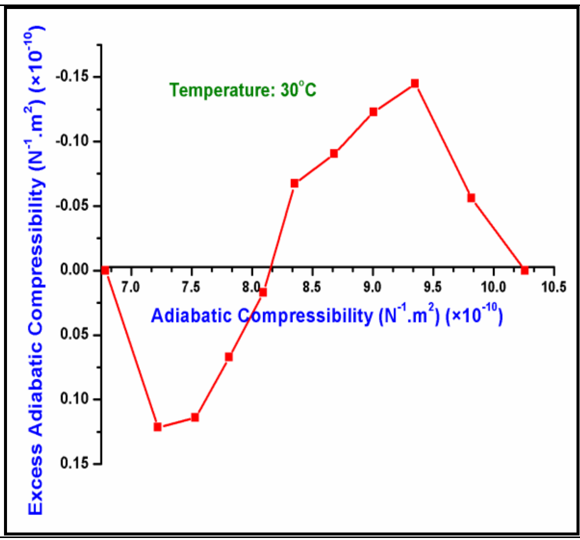

Fig.39: Relation between Adiabatic compressibility and Excess Adiabatic compressibility of Toluene + t-butanol solution

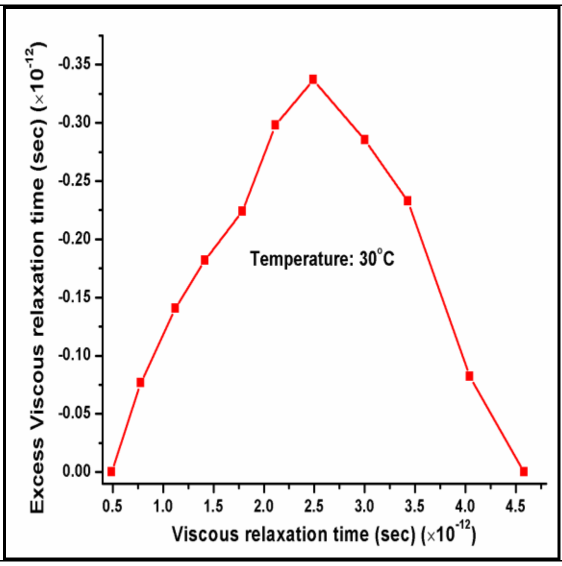

Fig.40: Relation between Viscous relaxation time and Excess Viscous relaxation time of Toluene + t-butanol solution

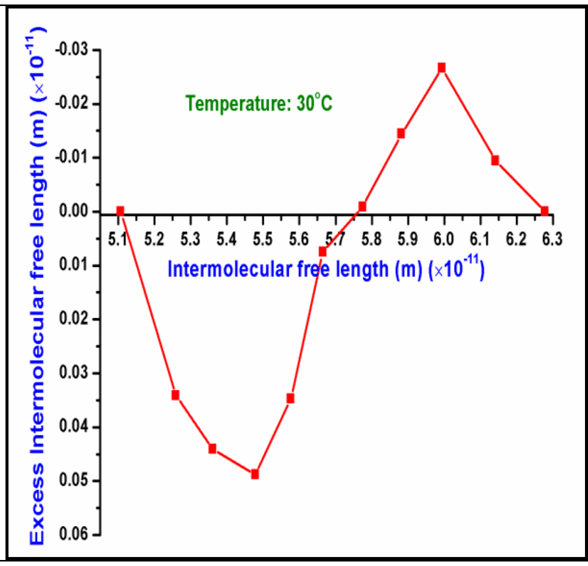

Fig.41: Relation between Intermolecular free length and Excess Intermolecular free length of Toluene + t-butanol solution

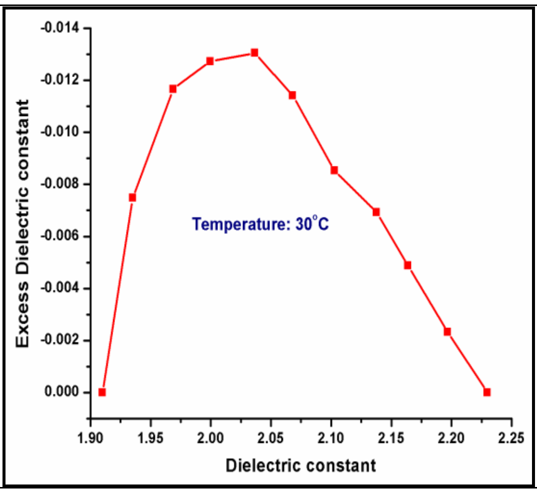

Fig.42: Relation between Dielectric constant and Excess Dielectric constant of Toluene + t-butanol solution

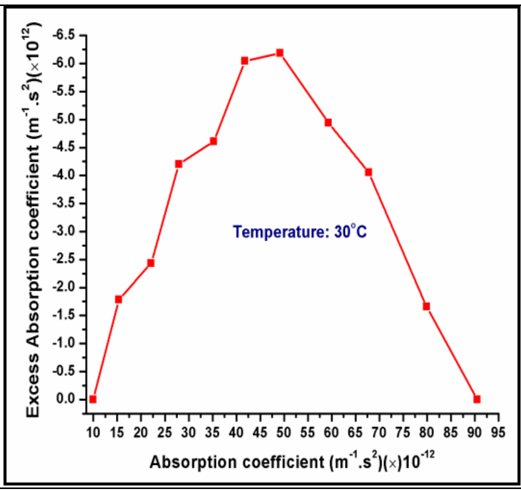

Fig.43: Relation between Absorption coefficient and Excess Absorption coefficient of Toluene + t-butanol solution

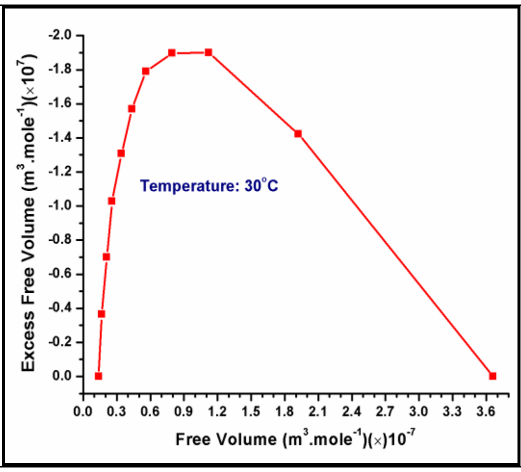

Fig.44: Relation between Free volume and Excess Free volume of Toluene + t-butanol solution

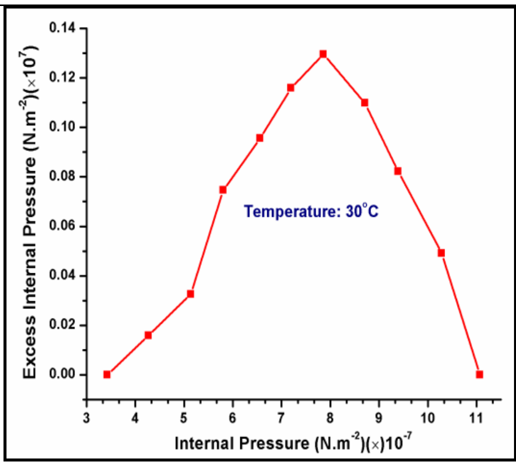

Fig.45: Relation between Internal pressure and Excess Internal pressure of Toluene + t-butanol solution

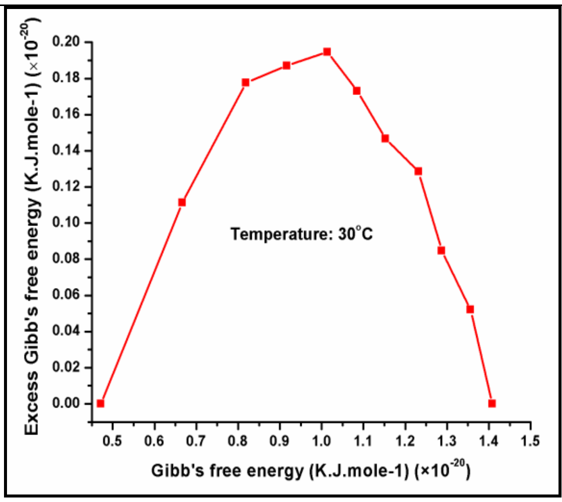

Fig.46: Relation between Gibb's free energy and Excess Gibb's free energy of Toluene + t-butanol solution

V. Conclusion

A novel multifunctional extrinsic fiber optic sensor has been developed to measure various chemical parameters of Toluene + tert-Butanol. The present sensor is calibrated for the measurement of refractive index, density, viscosity and ultrasonic velocity at 303K temperature and at the operating wavelength of 660nm. With the help of above experimentally measured parameters, the other parameters mole fraction, molar volume, molar refraction, dielectric constant, acoustic impendence, adiabatic compressibility, viscous relaxation time, intermolecular free length, absorption coefficient, Gibb's free energy, free volume, internal pressure have been calculated and presented graphically. The excess parameters which are arises out of the mixing of chemicals have been determined and related them with other parameters.

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