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ISSN: 2278-1862

Journal of Applicable Chemistry

2019, 8 (4): 1578-1585
(International Peer Reviewed Journal)

Study of Refractive Indices, Densities and Excess Properties of Binary Solutions of Alcohol and Water Using Intensity Modulated Fiber Optic Chemical Sensor

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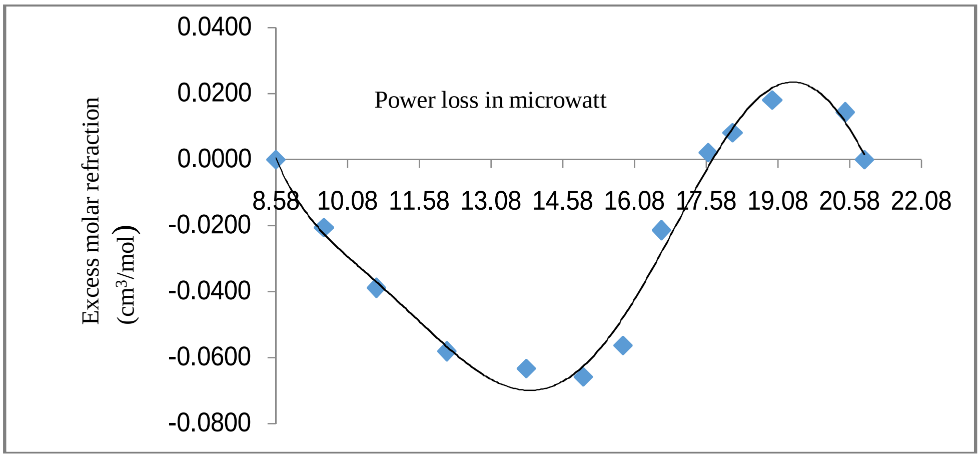
ABSTRACT

The refractive index, 'n' and density, 'ρ', of binary mixtures of alcohols and water; have been measured at a temperature of 298.15 K and atmospheric pressure. Molar volume and Molar refraction for the whole composition range were determined, using the obtained values of refractive index and density. Further, Excess molar refraction and Excess molar volume are calculated over the entire range. An intensity modulated fiber optic chemical sensor is designed to study the excess properties of the binary mixtures using the power loss over the entire range.

Graphical Abstract



Relation between power loss and excess molar refraction of ethanol water solution.

Keywords: Refractive index, Density, Fiber optic Chemical sensor, Change in output power, Power loss, Properties of binary mixtures, Excess Molar Properties.

INTRODUCTION

The physical properties of binary mixtures are studied for many reasons, of which the most important is to provide information about molecular interactions present in the liquid state [1]. Experimental data of physical properties such of densities, viscosities, or refractive indices are required for a complete understanding of the thermodynamic properties of liquid mixtures, as well as for practical chemical engineering work [2-6]. The studies of excess thermodynamic properties are of considerable interest in understanding the intermolecular interactions in binary liquid mixtures [7]. Knowledge of these properties is very much important in many practical problems concerning mass transport and fluid flow.

In the present work an attempt has been made to estimate the molar volumes (V_m), molar refraction (R_m) and excess molar volume (V_m^E) studies using optical fiber sensor. This has been done by removing the cladding portion in the middle along the length of optical fiber of known length (3cm) [8]. This portion where cladding has been removed called the sensing-length is exposed to chemical binary solutions of various compositions of water with alcohols (ethanol and 1-propanol) and the corresponding output power is noted. The calculated values of molar volumes (V_m), molar refraction (R_m), excess refractive index (n^E), excess molar volume (V_m^E) and excess molar refraction (R_m^E) and studies are related to the power loss. These relations are graphically represented and using these graphs, molar volumes (V_m), molar refraction (R_m), excess refractive index (n^E), excess molar volume (V_m^E), and excess molar refraction (R_m^E) can be studied using the output power and power loss.

MATERIALS AND METHODS

The arrangement for studying the variation of molar volume, excess molar volume, molar refraction, excess molar refraction with the power loss obtained by the variation of concentration of the solution surrounding the sensing region (bare core) of the fiber is shown in the block diagram in figure 1.

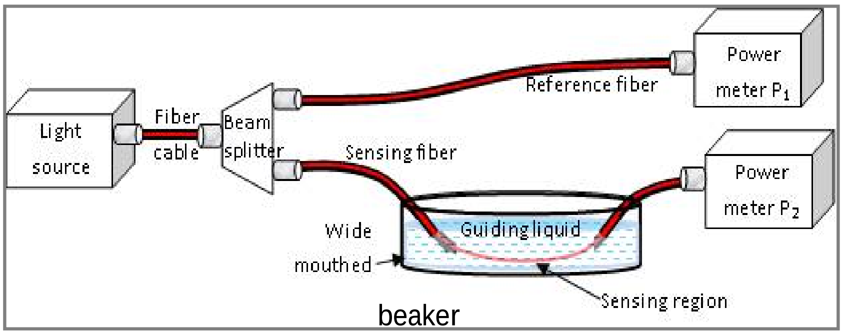


Figure 1. Block diagram for arrangement of fiber optic sensor.

The chemicals Ethanol and1-Propanolwere purchased from SPFine Ltd. (AR grade, 98% - 99% pure)**.**The optical fiber used in the experiment was a standard commercial step index polymer optical fiber (POF) with a Polymethyl methacrylate (PMMA) core of diameter 0.980 mm surrounded by a thin cladding layer of fluorinated polymer. The core refractive index (n_{core}) is 1.4900 and the numerical aperture 0.5. The refractive index of clad (n_{clad}) made of fluorinated polymer is 1.4036. Acetone was applied to the POF using a cotton bud and neutralized with the de-ionized Water. Acetone cleans the surface of the polymer. A 3cm cladding region in the middle of 1metre length plastic optical fiber was de-cladded using H_2SO_4 treatment. The light source used was 5 mW, 632.8 nm He - Ne laser (HNL050R) from Thor labs and the optical power meter was BD502A Handheld Optical Power Meter (-70~ +10dBm) from Fiberstore, China.

Experiment: Binary mixtures were prepared by mixing a known volume of each liquid in an airtight, stopper glass bottle. Refractive indices of pure liquids and binary mixtures were measured using thermostatically controlled Abbe's refractometer with accuracy 0.0001 units. Calibration was performed by measuring the refractive indices of doubly distilled water. Volumes were measured with an accuracy of 1 mL. Care was taken to avoid contamination during mixing. The densities of solutions were determined by pre-calibrated pycnometer (± 0.1%). The constant temperature of the prism box is maintained by circulating water from thermostat at (298 ±0.1) K. Power loss is the difference between reference power in power meter, P_1 (P_{ref}= 42 μW) and the output power obtained in power meter, P_2 (P_{out}). Power loss is determined at various concentrations of ethanol in water. The concentration is expressed in terms of mole fraction. The molar volume (V_m), molar refraction (R_m), excess molar volume (V_m^E) and excess molar refraction (R_m^E) were computed using the values of mole fraction, density (ρ) and refractive index (n), using the following formulae and related with power loss.

Molar volume of the solution; $$V_m = \frac{M_1 x_1 + M_2 x_2}{\rho_{solution}}$$

Molar refraction of the solution; $$R_m = \left(\frac{n^2-1}{n^2+2}\right) V_m$$

Excess Molar volume of the solution; $$(V_m^E) = \frac{x_1 . M_1 + x_2 . M_2}{\rho_{solution}} - \left(\frac{x_1 . M_1}{\rho_1} + \frac{x_2 . M_2}{\rho_2}\right)$$

Excess Molar refraction of the solution; $$R_m^E = R_m - (R_{m1}\, x_1 + R_{m2}\, x_2)$$

Where, M_1=Molecular weight of Ethanol = 46.07 $gmole^{-1}$(for first solution),
M_1= Molecular weight of 1-propanol = 60.09 g $mole^{-1}$(for second solution)
M_2 = Molecular weight of water =18.015 $gmole^{-1}$(in both solutions)

n = Refractive index and

$\rho_{solution}$= Density of solution

Table 1. Table showing mole fraction, density, refractive index, output power, power loss Molar volume, Molar refraction and excess properties at various concentrations of ethanol-water binary solution.

S. No.	Mole fraction		Density (ρ) g/ml	Refractive Index (n)	Molar volume (V_m) Cm^3/mol	Molar refraction R_m Cm^3/mol	Excess Molar volume (V_m^E)	Excess Molar refraction R_m^E	P_{out} μW	Power loss =(42-P_{out}) μW
	Ethanol (X_1)	Water (X_2)								
1	0.0000	1.0000	0.99703	1.3324	18.0690	3.7106	0.0000	0.0000	33.42	8.58
2	0.1010	0.8990	0.96005	1.3457	21.7164	4.6210	-0.4544	-0.020663	32.41	9.59
3	0.2001	0.7999	0.93002	1.3535	25.4070	5.5161	-0.7885	-0.03894	31.32	10.68
4	0.2987	0.7013	0.90349	1.3574	29.2147	6.4057	-0.9852	-0.05818	29.84	12.16
5	0.3332	0.6668	0.89481	1.3582	30.5798	6.7185	-1.0213	-0.06339	28.18	13.82
6	0.4087	0.5913	0.87673	1.3595	33.6263	7.4120	-1.0410	-0.06589	26.99	15.01
7	0.5051	0.4949	0.85563	1.3604	37.6164	8.3101	-0.9661	-0.05634	26.16	15.84
8	0.6030	0.3970	0.8366	1.3614	41.7550	9.2474	-0.8035	-0.02148	25.35	16.65
9	0.6664	0.3336	0.82577	1.3618	44.4566	9.8555	-0.6768	0.00220	24.38	17.62
10	0.7032	0.2968	0.82006	1.3617	46.0251	10.2007	-0.6028	0.00817	23.86	18.14
11	0.7956	0.2044	0.80752	1.3614	49.9449	11.0623	-0.4306	0.01809	23.03	18.97
12	0.9075	0.0925	0.7954	1.3609	54.6579	12.0899	-0.2672	0.01426	21.51	20.49
13	1.0000	0.0000	0.78508	1.3593	58.6819	12.9283	0.0000	0.00000	21.11	20.89

These studies are related to the power loss in optical fiber sensor. These relations are graphically represented and using these graphs the trend of change in molar volume (V_m), molar refraction (R_m), excess molar volume (V_m^E), and excess molar refraction (R_m^E) can be studied using the power loss.

RESULTS AND DISCUSSION

It is observed from figure 2 that; as concentration of ethanol or 1-propanol in terms of mole fraction in water-alcohol solution increases the refractive index of solution increases which leads to increase in power loss. The increase in power loss is from 8.58 μW to 20.89 μW in ethanol-water solution; and from 8.92 μW to 22.50 μW in 1-propanol-water solution. It is illustrated in figure 3. Hence, using power loss, the change in properties like molar volume and molar refraction can be studied in binary water-alcohol solutions. As power loss increases from 8.58 µW to 20.89 µW in ethanol-water solution the molar volume of ethanol-water solution increases from18.069 cm^3/mol to 58.682 cm^3/mol; and in 1-propanol-water solution, as power loss increases from 8.92 µW to 22.50 µW, the molar volume of increases from 18.069 cm^3/mol to 75.144 cm^3/mol.

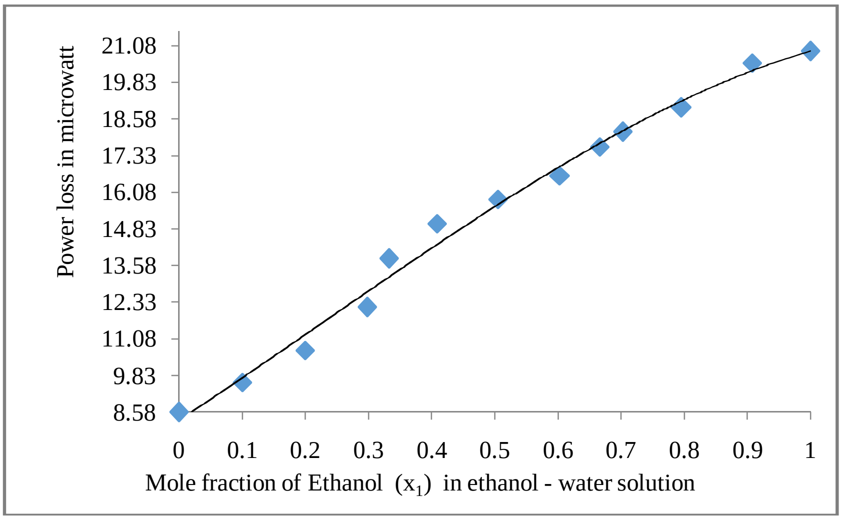


Figure 2. Graph showing relation between mole fractions of ethanol in ethanol-water solution and power loss.

For the same concentration of alcohol in water the molar volume is more in case of 1-propanol system than in ethanol system. This may be due to more number of carbon atoms and higher molecular weight of 1-propanol, as number of atoms has been increased in propanol, the interactions between them also increases. As power loss increases from 8.58 µW to 20.89 µW in ethanol-water binary system, the molar refraction of ethanol-water solution increases from 3.710 cm^3/mol to 12.928 cm^3/mole and as power loss increases from 8.92 µW to 22.50 µW in 1-propanol-water binary system, the molar refraction of 1-propanol-water solution increases from 3.710 cm^3/mole to 17.541cm^3/mol, as illustrated in figures 4 to 9.

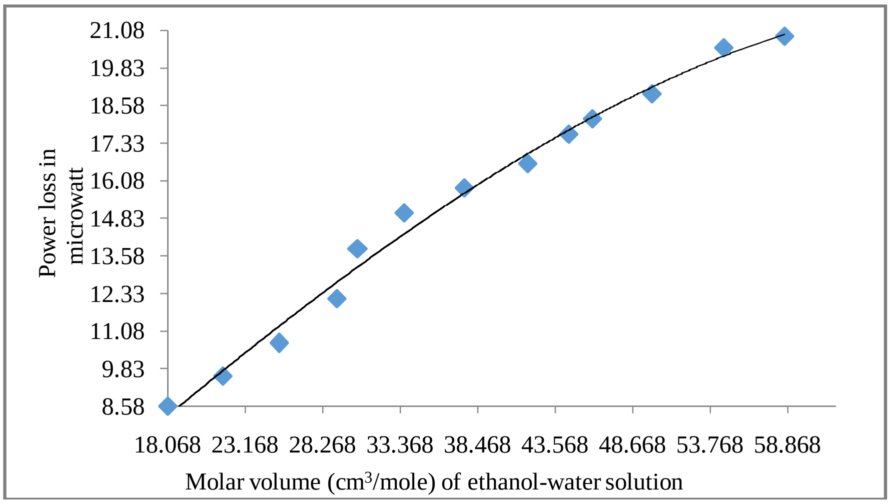


Figure 3. Graph showing relation between molar volume of ethanol-water solution and power loss.

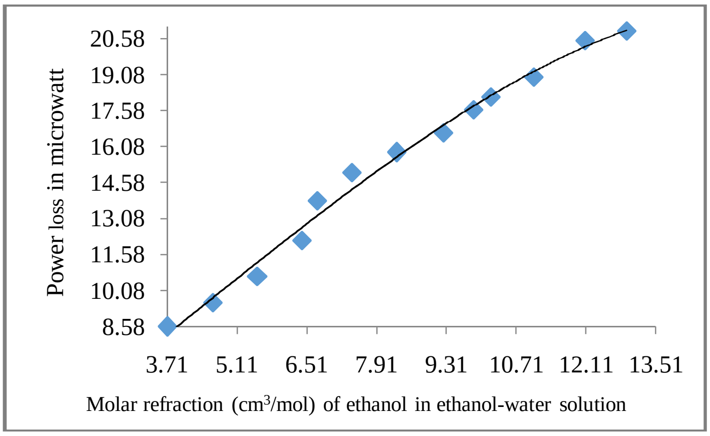


Figure 4. Graph showing relation between molar refraction and power loss in ethanol-water solution

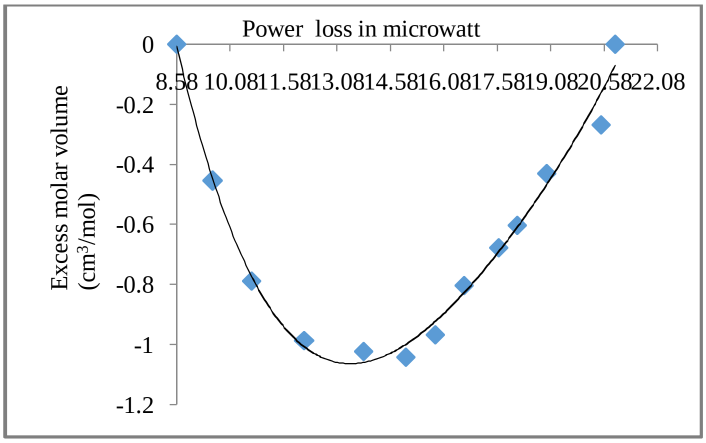


Figure 5. Graph showing relation between excess molar volume of ethanol-water solution and power loss

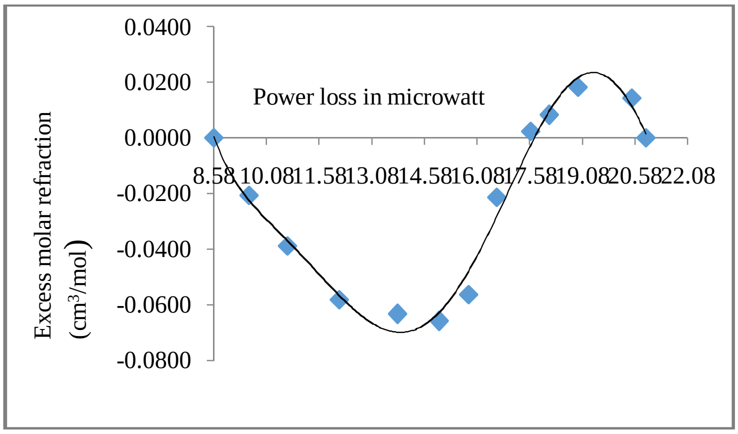


Figure 6. Graph showing relation between power loss and excess molar Refraction of ethanol-water solution

It can be seen from figure 5 that; as concentration of ethanol in terms of mole fraction increases from 0 to 1 corresponding to the power loss 8.58 µW to 20.89 µW, the excess molar volume decreases to a minimum of -1 at power loss 13.01 µW with corresponding mole fraction of ethanol 0.31. Also, it is clear from figure 10 that: as concentration of propanol in terms of mole fraction increases from 0 to 1 corresponding to the power loss 8.92 µW to 22.5 µW, the excess molar volume decreases to a minimum of -0.6 at power loss 18µW with corresponding mole fraction of propanol 0.4.

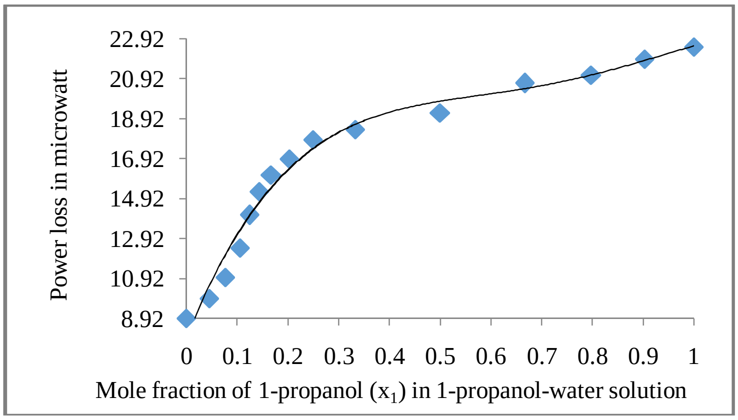


Figure 7. Graph showing relation between mole fraction of 1-Propanol in 1-propanol-water solution and power loss.

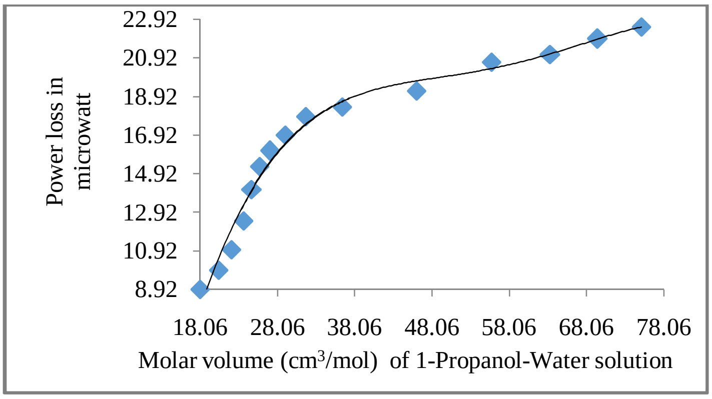


Figure 8. Graph showing relation between molar volume of 1-Propanol-Water solution and power loss.

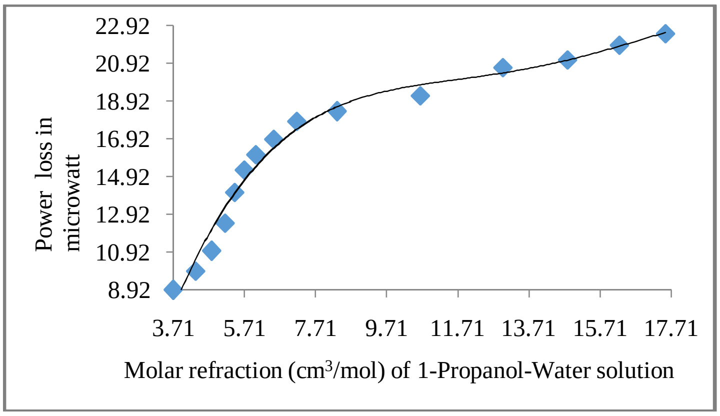


Figure 9. Graph showing relation between molar refraction of 1-Propanol-Water solution and power loss in the power meter

Figure 6 above illustrates that, for ethanol-water system, the negative peak of excess molar refraction occurs at -0.066 cm^3/mole corresponding to the power loss 15.02 µW that is at a mole fraction of ethanol 0.41 and the positive peak 0.002 occurs at power loss 17.62 µW or mole fraction of ethanol 0.66. At higher concentration of propanol above 0.67 mole fraction or corresponding power loss 17.58

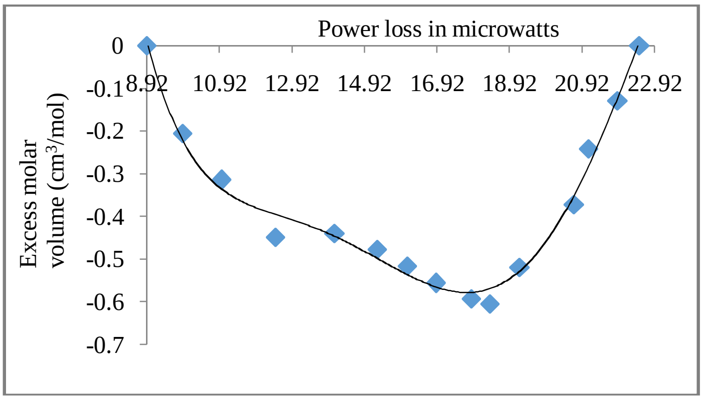


Figure 10. Graph showing relation between power loss and excess molar volume of 1-Propanol-Water solution.

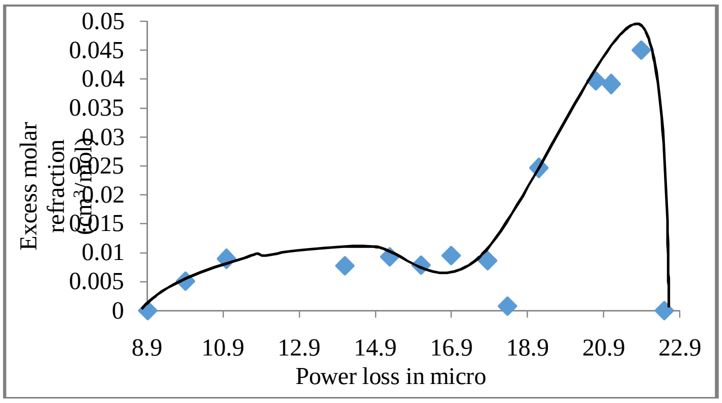


Figure 11. Graph showing relation between power loss and excess molar refraction of 1-Propanol-Water solution.

Table 2. Table showing mole fraction, density, refractive index, output power, power loss Molar volume, Molar refraction and excess properties at various concentrations of 1-Propanol-water solution

S. No.	Mole fraction		Density (ρ) gm/ml	Refractive Index (n)	V_m Cm³/mol	R_m Cm³/mol	(V_m^E)	R_m^E	P_{out} μW	Power loss = (42- P_{out}) μW
	1-Propanol (X₁)	Water (X₂)								
1	0.0000	1.0000	0.99703	1.3324	18.0689	3.7106	0.00000	0.00000	33.08	8.92
2	0.0452	0.9547	0.97429	1.3449	20.4426	4.3408	-0.2061	0.00507	32.09	9.91
3	0.0769	0.9231	0.95970	1.3515	22.1432	4.7830	-0.3148	0.00887	31.01	10.99
4	0.1059	0.8942	0.94959	1.3553	23.6639	5.1612	-0.4493	-0.01398	29.54	12.46
5	0.1243	0.8757	0.94020	1.3586	24.7236	5.4374	-0.4397	0.00769	27.90	14.10
6	0.1433	0.8567	0.93302	1.3610	25.7707	5.7017	-0.4771	0.00926	26.72	15.28
7	0.1670	0.8330	0.92459	1.3634	27.0842	6.0280	-0.5163	0.00783	25.90	16.10
8	0.2030	0.7971	0.91263	1.3666	29.0988	6.5275	-0.5564	0.00940	25.10	16.90
9	0.2499	0.7499	0.89890	1.3698	31.7385	7.1753	-0.5935	0.00850	24.14	17.86
10	0.3331	0.6671	0.87812	1.3734	36.4760	8.3181	-0.6047	0.00069	23.62	18.38
11	0.5002	0.4998	0.84734	1.3790	46.0984	10.6530	-0.5196	0.02459	22.80	19.20
12	0.6670	0.3331	0.82629	1.3819	55.7662	12.9749	-0.3720	0.03971	21.30	20.70
13	0.7979	0.2021	0.81409	1.3831	63.3673	14.7847	-0.2421	0.03909	20.90	21.10
14	0.9034	0.0966	0.80611	1.3840	69.5011	16.2497	-0.1297	0.04505	20.10	21.90
15	1.0000	0.0000	0.79966	1.3833	75.1444	17.5407	0.0000	0.00000	19.50	22.50

μW, the peak is positive and below this concentration peak is negative. At mole fraction 0.67, both the interactions are equal and cancel each other, hence excess molar refraction becomes zero. At mole fraction 0 or 1 of ethanol, there is only one liquid either water or ethanol, no molecular inter actions occur between water and ethanol hence the excess molar refraction becomes zero at mole fraction 0 or 1 at corresponding power loss 8.58 µW and 20.89 µW. But, in case of propanol-water system, it is seen from figure 10, 11 that the positive peak of excess molar refraction occur at 0.46 cm^3/mole corresponding to the power loss 21.8 µW that is at a mole fraction of propanol 0.46. At mole fraction 0 or 1 of propanol, there is only one liquid either water or propanol, no molecular inter actions occur between water and ethanol; hence the excess molar refraction becomes zero at mole fraction 0 or 1 at corresponding power loss 8.58 µW and 20.89 µW.

APPLICATION

The study of excess molar volume and excess molar refraction may be used to select proper composition ratio in pharmaceutical industry.

CONCLUSION

Molecular interactions between the constituent molecules depend on mole fraction. The peak interaction in the composition can be studied using fiber optic sensor.

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