Estimation of LiBr-H2O Using Multimode Interference (MMI)

E.E. Antúnez-Cerón[1], M.A. Basurto-Pensado*[1], A.R. Mejía-Aranda[1],R.J. Romero[1],
J.J. Sánchez-Mondragón[2],H.H. Cerecedo-Núñez[3], A. Ochoa-Zezzati[4],

[1] Centro de Investigación en Ingeniería y Ciencias Aplicadas
Universidad Autónoma del Estado de Morelos
Cuernavaca, Mor., México
*mbasurto@uaem.mx
[2] Instituto Nacional de Astrofísica, Óptica y Electrónica
Instituto de Investigaciones Eléctricas
Tonantzintla, Pue., México
[3] Universidad Veracruzana
Xalapa, Veracruz, México.
[4] Universidad Autónoma de Ciudad Juárez
Cd. Juárez, Tamaulipas, México

ABSTRACT
We use multimode interference (MMI) as an alternative optical technique to estimate lithium bromide (LiBr) concentration, of the work pair LiBr-H_2O, in absorption heat pumps (AHP). The sensing element is a singlemode-multimode-singlemode (SMS) fiber optic structure. This is fabricated by splicing a precisely dimensioned multimode fiber (MMF) section between two singlemode fibers (SMFs). The operation principle is based on the multimode interference (MMI) effect occurring in the MMF section. For that purpose, different concentrations of the mixture were prepared (from 44.30% to 60.69%) to study their optical response. The input field profile entering the sensing element, which is the naked (no cladding) MMF section of the SMS fiber structure, produced different transmitted intensity responses for each of these concentrations. Thus the optical characterization of the mixture was used to establish a mathematical relation to estimate the LiBr concentration. A linear fit for solutions with concentrations ranging from 43.30% to 50.87% and refractive indices between 1.421 and 1.439 is demonstrated.

Keywords: multimode interference, fiber optic, refractive index.

1. Introduction

Bromide-water (LiBr-H_2O) mixture is widely used as a refrigerant solution in absorption heat pumps (AHP) and heat transformers. AHP represent a suitable technology for low-quality energy recovery, which in most cases is released into the environment, producing a noxious impact [1]. Actually, LiBr concentration is not calculated *"in situ"* in the AHP's. There are two conventional techniques to estimate it: Refractometry and the Dühring Diagram. It is of important to know the LiBr concentration to prevent reaching the crystallization point of the solution at the given operating conditions. With this, we will avoid severe damage to the AHP components. An alternative method to estimate LiBr concentration is using operating sensors based on the solution optical properties (e.g. the refractive index, n). An optical methodology provides information on the identity of the atomic/molecular species in the analyte (qualitative analysis) or quantitative information such as the amount of one or more components (quantitative analysis) [2-3]. Multimode interference (MMI) effect is proposed as a technique which relates the refractive index (n) of the LiBr-H_2O mixture and the LiBr concentration.

Recently, MMI effects occurring in SMS (singlemode-multimode-singlemode) fiber structures were investigated and used for both sensing and signal processing applications [4-9]. These optical devices offer an all-fiber solution with the advantages of easy of manufacturing, packaging and interconnection to other optical fibers. In addition, they offer the possibility of sensing by a simple system based on intensity measurements.

2. Experimental Details

2.1. Principle of Operation

A useful basis for getting a better understanding of MMI in a multimode waveguide is the phenomenon of self-imaging, which loosely can be defined as the property of multimode waveguides of reproducing the input field, at periodic given distances, by constructive interference. The self-imaging phenomenon in a waveguide, due to MMI, was initially studied and described elsewhere [10]. The specific characteristics of the constructive interference in a realistic waveguide leads to single or multiple images of the input field and images and pseudoimages at periodic intervals along the propagation direction of the waveguide.

Therefore the MMF section of a SMS fiber structure can support many guided modes, and thus, an input field coupled to the MMF can reproduce a single self-image or multiple-images (pseudo-images) at regular intervals along the MMF waveguide due to constructive interference between all guided modes. In order to obtain a self-image, the phase difference between all guided modes has to be an integer multiple of 2π so that all modes interfere in phase and the input field can be reproduced at the end of the MMF section. This effect has been extensively studied [10] and the length *(L)* where self-images are formed in the MMF section is given by:

$$\mathbf{L_{self-image}} = p\frac{16 n_{core} a^2}{\lambda}\ ,\ p = 0,1,2,\ldots \qquad (1)$$

The self-image distance *(L)* is a function of the physical properties of the waveguide (the refractive index n_{core} and the core radius a of the MMF section) the operating wavelength *(λ)*, and the parameter p that denotes the constructive interference number (self-image). Such constructive interference can occur at periodic intervals defined by p (p = 1/4, 1/2, 1/3), at these lengths the formed images are called pseudo-images. A self-image will show a profile of a narrow width and a high amplitude, while pseudo-images will show a wide width and a low amplitude (e.g., p = 1/4); the closer to a value of p = 1, the narrower is the width of the profile and the amplitude increase. In this research we focused our interest in the particular value of p = 1/4, since this value is characterized by a wide gaussian output field profile. This sensing technique is based in obtaining a shift of the signal with the change of the environment.

2.2. Analyte Preparation

Different composition ratios of thirteen LiBr-H2O concentrations were prepared (Table 1); all in a total volume of 10 ml. Table 1 also shows the refractive index of each one of these concentrations, which was determined by refractometry.

Fig.1 shows the experimental setup for MMI, which consists of a butterfly laser diode (1555 nm) and its driver, the SMS fiber structure (sensing element), an InGaAs photodetector (FG04A, Thorlabs), the filtering and signal amplification electronics, a data acquisition board (USB-6259, National Instruments) and a graphical user interface (GUI) implemented in LabVIEW.

Sample	Refractive index (n)	LiBr concentration (% wt)
1	1.421	44.0
2	1.425	45.86
3	1.426	46.24
4	1.439	50.87
5	1.444	52.49
6	1.447	53.41
7	1.4518	54.83
8	1.453	55.17
9	1.457	56.27
10	1.4601	57.05
11	1.466	58.53
12	1.47	59.43
13	1.476	60.69

Table 1. LiBr-H2O solutions prepared at different ratios of LiBr

2.3 SMS Fiber

We use a SMS optical fiber such that the MMF and SMF sections have a step refractive index profiles. The sensing element (MMF) has a core diameter of 125 µm, without cladding, and a refractive index of 1.440. The SMF sections have a core diameter of 10 µm and a diameter, including the cladding, up to 125 µm (to match the core diameter of the MMF). The respective refractive indexes are 1.450 for the cladding and 1.461 for the core. The SMS fiber was operated at a wavelength of 1555 nm. The length *(L)* of the MMF section was 14.55 mm to reproduce the first pseudo-image, of the input profile, at the exact output end of the MMF section. This particular type of optical fiber has a unique characteristic: the core is exposed, i.e., no cladding surrounds the core in the sensing area (MMF section). A schematically diagram of the SMS fiber used is shown in Figure 2.

The MMF section plays the sensing role as shown in Figure 2, since this section has no cladding and its exposed core acts as a sensing element when is in contact (or surrounded) with any medium, material, or as in our case, a LiBr-H_2O solution. The solution acts as the cladding of the core to produce a transmitted intensity response at the distant end of the SMS fiber. This effect is produced due to the MMF section and therein is dimensioned to a specific length (14.55 mm) to reproduce only a pseudo-image of the input profile. The shift experienced for this pseudo-image will generate different transmitted intensity responses for each concentration of the mixture in which the sensing fiber was immersed.

The SMS fiber was operated at 1555 nm. The output profile of the self-image at the output end of the SMS fiber structure is shown in Figure 3, this output profile corresponds to the spectral response of the SMS fiber in air (as cladding) at the abovementioned wavelength. We expect that this profile experiences a shift (in the direction of the waveguide propagation) when the SMS (specifically the MMF section) is immersed in different concentrations of the LiBr-H_2O mixture, thus obtaining larger intensity optical responses.

3. Results and Discussion

The transmitted intensity response of the SMS fiber in the experimental setup (Figure 1) was characterized using its equivalent voltage response. On the other hand, we knew that each solution of the mixture had a different refractive index (n) thus each generated response was supposed to show a difference in the intensity. The results obtained with MMI (as voltages responses) are shown in Figure 4.

From Figure 4, it can be observed three trends in the experiment as we increase in the concentration. First: the voltage signal increases for the four first concentrations. Second: the voltage signal decreases as we increase in the concentration of the mixture, and third: it is observed an increase in the voltage signal for the highest concentrations.

Such non monotonic behavior finds its explanation on the optical fibers operation principle. It establishes that for guiding, the refractive index of the core must be greater than the refractive index of the cladding; that is $n_{core} > n_{cladding}$. We could estimate experimentally the ncore of the MMF section and it was found to be close to 1,440. Thus it can established that an increase in the LiBr concentration also increases the refractive index of the solution. At a particular concentration, the n_{core} refractive index will be overcome by the solution’s refractive index (cladding) causing light dispersion off the core of the MMF section.

The first tendency involves solutions of LiBr-H_2O at concentrations between 44.30% and 50.87%. For these concentrations, the voltage response increases although it is a small voltage range (from 0,821 to 0,874 V). It is noteworthy to notice that at those concentrations the corresponding refractive indexes ranges between 1,421 and 1,439.

Figure 5 shows that the LiBr estimation for concentrations lower than 50.87% can be obtained from Equation 2, which has a quadratic adjustment factor of 0.999 and where the variable “V” stands for the voltage response of each concentration.

$$\%_{LiBr} = 123.33(V) - 56.91 \tag{2}$$

The second trend occurs for concentrations between 52,49% and 57,05% and refractive indices ranging between 1,4601 and 1,444. It can be observed that the voltage signal decreases significantly from 0.86 to 0.312 V.

Figure 6 shows the quadratic approximation for these concentrations. For these data, the LiBr concentration can be approximated by the second order expression (Equation 3), in which the variable *“V”* stands for the voltage response obtained for each concentration. The quadratic adjustment factor for Equation 3 is approximately of 0.925.

$$\%_{LiBr} = -17.759(V^2) + 13.472(V) + 54.485 \quad (3)$$

Finally, the increasing trend of the voltage response for the highest concentrations (58.53%, 59.43% and 60.69%) is due to the solution's cristalinity. There, our conveniently simple fiber concepts of high concentration mixtures, and therein high mixture refractive index with respect to the MMF fiber section, are not straightforwardly valid anymore. However, the monotonic behavior shows an attractive region that we intend to further optically explore and report elsewhere.

4. Conclusions

Based on an optical property, meaning refractive index (n) of the mixture of LiBr-H2O, we have proposed an alternative method to estimate the LiBr concentration used in the operation of a heat transformer. The sensing device is proposed as a prototype of easy construction, low cost and quite convenient usage. Its implementation may represent a new reliable and convenient technique for determining the concentration of LiBr "in situ" in the equipment, improving existing alternatives. The limit observed for this Optical method seems to be able to be further extended once the structural conditions are taken into account, and that is quite an attractive perspective.

Using MMI effect based on an optical property of the analyte the concentration of one of the compounds can be estimated quantitatively establishing a mathematical equation which relates the value of the refractive index with the concentration of the compound of interest.

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