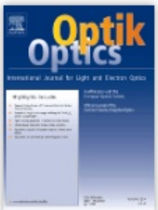

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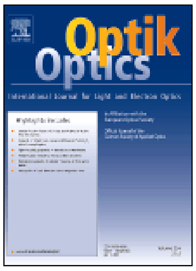

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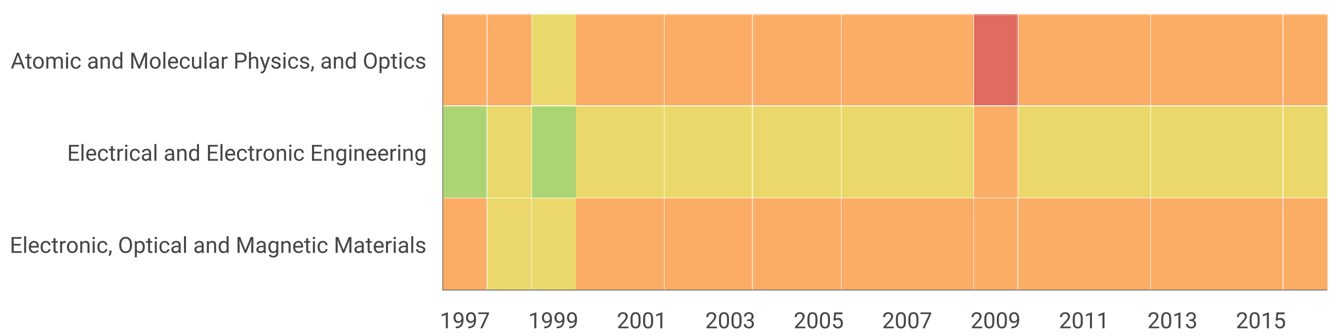


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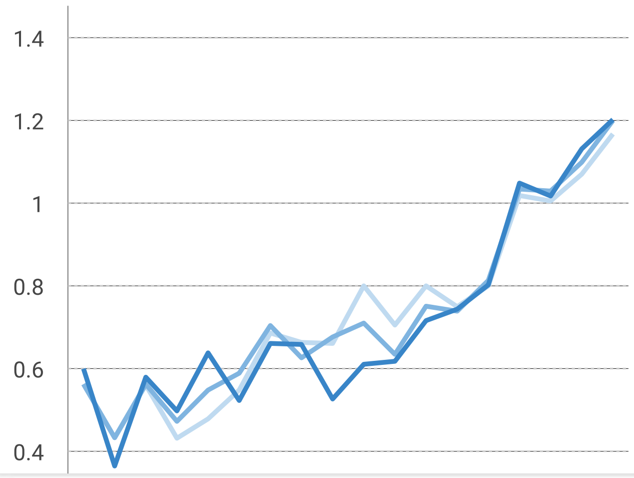


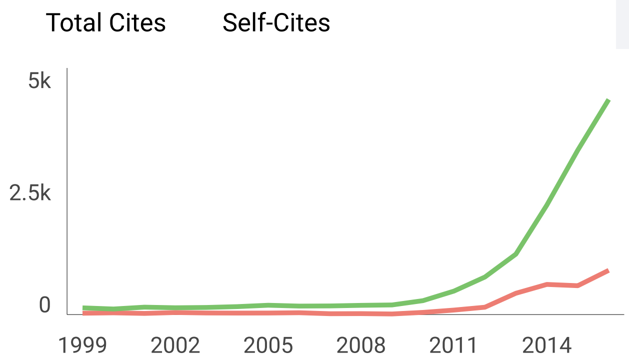


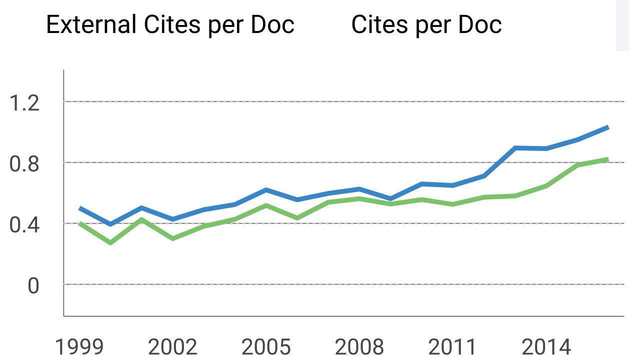


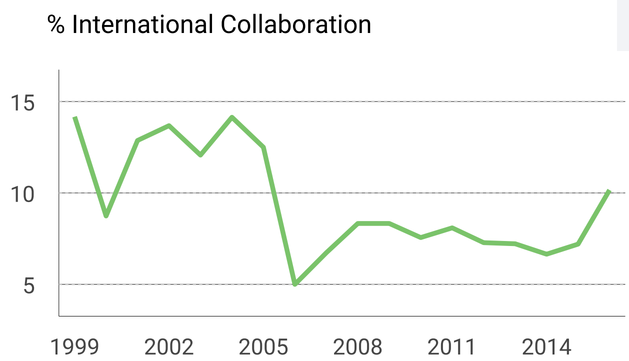


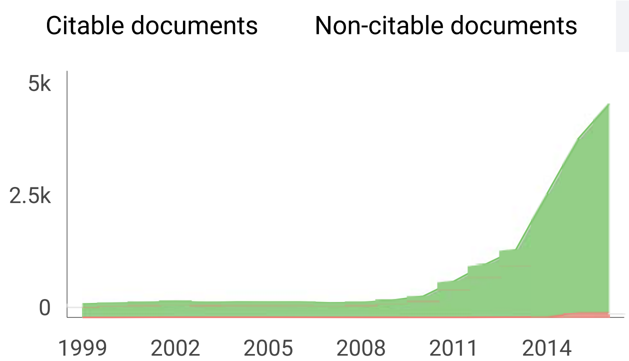


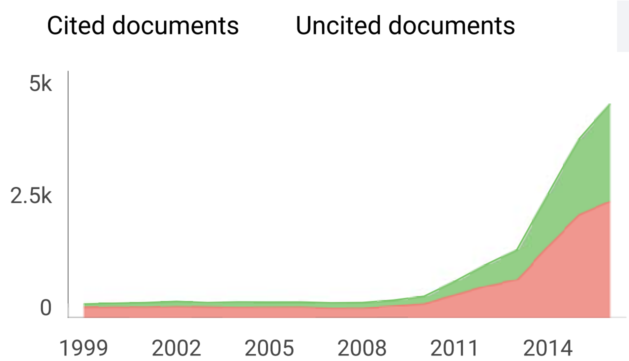


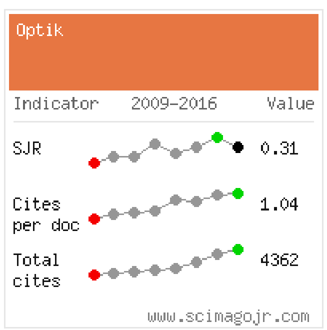


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Original research article

# Detection of magnesium ion concentration using fiber coupler based displacement sensor with concave mirror target

M. Yasin[a,*], Samian[a], M. Khasanah[b]

[a] *Physics Department, Faculty of Science and Technology, Airlangga University, Surabaya 60115, Indonesia*
[b] *Chemistry Department, Faculty of Science and Technology, Airlangga University, Surabaya 60115, Indonesia*

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ABSTRACT

Detection of magnesium ion concentration was successfully demonstrated using a fiber coupler based displacement sensor probe in conjunction with a concave mirror target. Analysis of peak voltage result, which was obtained by moving a sensing port displacement from a fixed concave mirror (CM) was found to be useful to detect a magnesium ion concentration, which is filled in between the probe and target. The proposed sensor is capable for measuring magnesium ion with variation of concentration 0–5%. The resolution of the sensor can be achieved at 0.2%. It was also observed that the use of CM with a longer focal length improves the sensitivity of the sensor. The high sensitivity, the small size, the ease fabrication process, and the bio-compatibility of the proposed device are appealing characteristics that makes it ideal for practical bio-sensing applications.



## 1. Introduction

Detections of refractive index and concentration of liquid solution have widely been reported using various fiber-optic sensors [1–5]. Owing to the intrinsic characteristics of the optical fiber, these sensors are in general simple to fabricate, compact, robust, immune to electromagnetic radiation, chemical and biological inert, and can be integrated in complex networks for real-time multiple parameter sensing. In recent years, many important advances were achieved in the fiber optic sensor technology; in terms of sensitivity, resolution, dynamic range, response time, signal to noise ratio and fabrication techniques. These advances have also promoted the development of optical fiber chemical sensors and biosensors [1,2]. For instance, the side-emitting technique was conducted using fiber optic micro-bend [3] and tapered fiber [4] to detect refractive index of chlorinated water and concentration of uric acid, respectively. Optical fibers coated with silver thin layer [5] and nanocomposite of ZnO-polypyrrol [6] were also used to detect concentration of uric acid and manganese ion based on surface plasmon resonance (SPR). Coreless fiber [7] and thin core fiber [8] connected to single mode fiber were used to detect concentration of sucrose and refractive index of solution, respectively.

A method based on displacement sensor can also be used to measure the concentration or refractive index of solution. For instance, a displacement sensor with a bundled fiber probe was capable of measuring refractive of solution [9], glucose concentration [10], calcium [11] and salinity [12]. This type of sensor works based on detection the output voltage as the displacement between sensor probe and mirror immersed in liquid of the solution sample is varied. Fiber coupler is an

* Corresponding author.
*E-mail address:* yasin@fst.unair.ac.id (M. Yasin).

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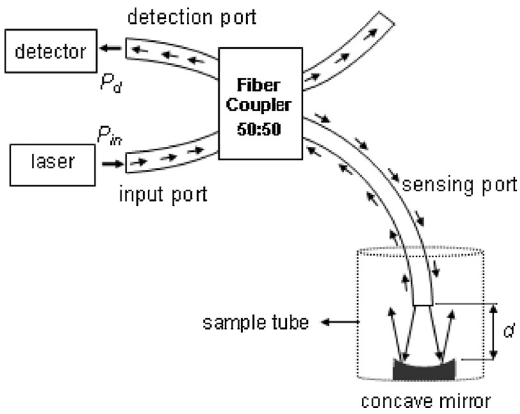


**Fig. 1.** Design of magnesium ion sensor using fiber coupler with concave mirror as reflector.

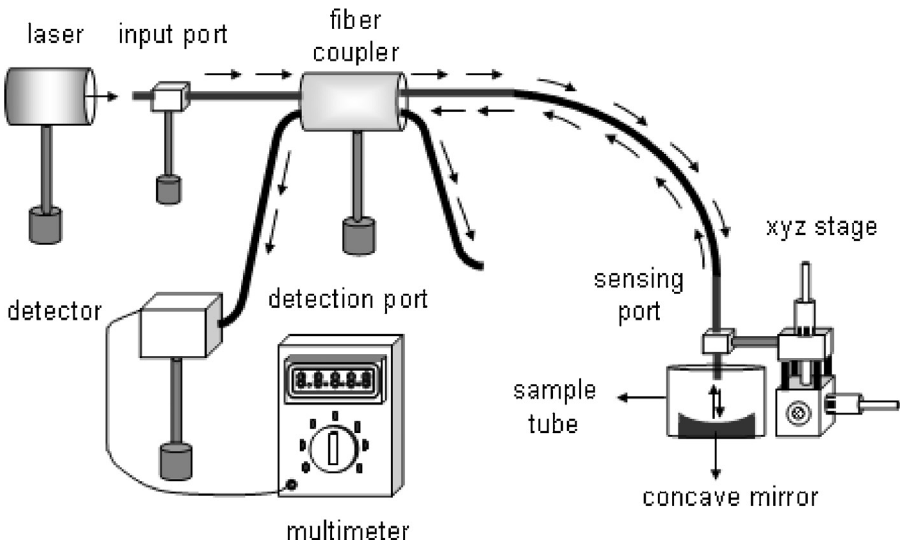


**Fig. 2.** Experimental setup for magnesium ion concentration sensor.

optical device that can be used to split a beam of light. It was used as a displacement sensor using a mirror as a target [13]. Based on the displacement sensor, fiber coupler was also employed as a level sensor [14] and a Rhodamine B concentration sensor [15] using a concave mirror (CM) as a target in conjunction with a green light source.

In this paper, we propose a new displacement sensor for measuring magnesium ion concentration using a fiber coupler as a probe and a concave mirror as a target. The magnesium ions detection is explored in this study since the ion is very important for the human in energy metabolism process, protein synthesis, muscle contraction, fat breakdown, DNA stability, and cell growth. Lack of magnesium ions in the body will affect health even can cause disease and cancer [16]. Therefore, the magnesium ions sensing device is becoming important especially for the food and beverage industry in order to meet the needs of magnesium ions that are perceived by the body.

## 2. Working principle of the sensor

Mechanism of magnesium ion detection using fiber coupler and concave mirror (CM) is shown in Fig. 1. Light source of the laser is coupled to input port of the coupler, part of the output light beam from the sensing port ($P_e$) enter to concave mirror. Medium between sensor port and CM is the testing sample. Partial of the reflected light beam from CM passed through a sensing port ($P_b$) and then transmitted to the detection port ($P_d$). The distance between sensing port and CM is attributed by $d$. If position of sensing port is changed in relation to CM, then the detected optical power as function of $d$ is given by [15];

$$P_d = P_0\left(1-\exp\left(-\frac{2(d-f)^2/f^2}{\left(\frac{d^2-2df}{(d-f)a}\tan\sin^{-1}\left(\frac{NA}{n}\right)+1\right)^2}\right)\right) \tag{1}$$

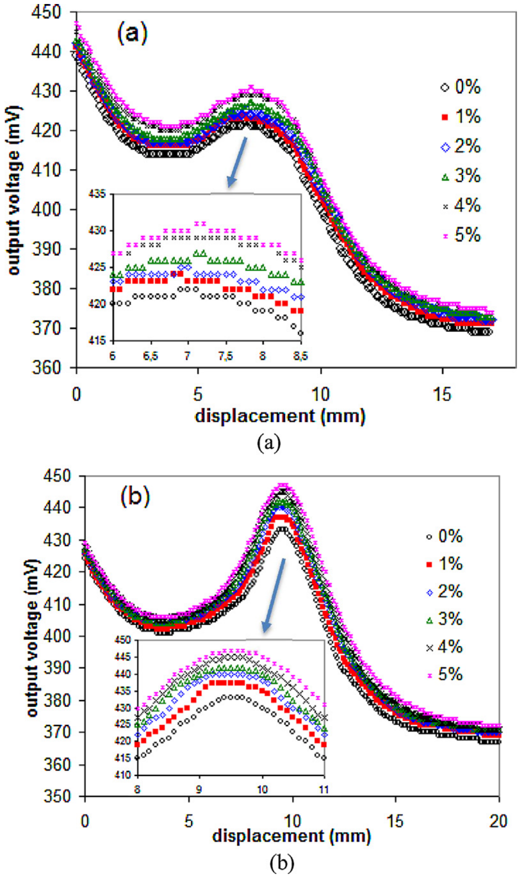


**Fig. 3.** Output voltage against the the displacement of sensing port as (a) CM 1 and (b) CM 2 was used as a target.

where $a$, $NA$, $f$ and $n$ is core of radius, numerical aperture, focal length of CM and refractive index of medium between sensing port and CM, respectively. $P_0$ can be written by equation as follows;

$$P_0 = 1.15cr\,(1 - cr)\left(10^{-0.1Le} - 2 \times 10^{-0.1D}\right)^2 P_{in}, \tag{2}$$

where $cr$, $L_e$, and $D$ are coupling ratio, excess loss, and directivity of fiber coupler respectively. While $P_{in}$ optical power of the laser which is coupled to input port [13].

Optical power of laser is measured by an optical detector using digital voltmeter in term of output voltage ($P_d$). Output power is proportional to output voltage. When Eq. (1) is simulated, we can obtain the curve showing the relationship between output voltage ($V$) and $d$. The curve also indicates a peak voltage at a certain location. The value of $V_p$ increase with refractive index of medium. If we assumed that refractive index is a linear function to magnesium ion concentration in solution as a medium, then the test sample of magnesium ion concentration can be read from the peak voltage. Variation of position scanning between sensing port and concave mirror is used to obtained peak voltage.

## 3. Experimental Setup

The schematic experimental setup for the proposed magnesium ion concentration sensor is shown in Fig. 2. It consists of a He-Ne laser (with wavelength of 632.8 nm and maximum power of 10 mW), fiber coupler and silicon detector. The fiber coupler probe was constructed from a multimode plastic fiber with structure 2 × 2, diameter of 1 mm, 50/50 splitting ratio, 4 dB insertion loss and 1.6 dB excess loss. A CM with two different focal length 4.5 and 6 mm was used as reflector. CM was placed on the bottom sample tube with diameter of 4 cm and 3 cm height.

The positioning of the fiber coupler sensing port was accomplished by mounting it on a micro-displacement meter, which was rigidly attached to a vibration free table. Light from the fiber coupler input port was coupled into the sensing port. The signal from sensing port was measured by moving the probe away from the zero point, where the reflective surface of concave mirror and the probe were in close contact. The signal from the optical detector was converted into voltage and was measured by a digital voltmeter. The output intensity was measured by changing the position of the fiber coupler sensing port, which functions as probe from 0 to 15 mm in step of 100 μm. The measurements were carried out for magnesium

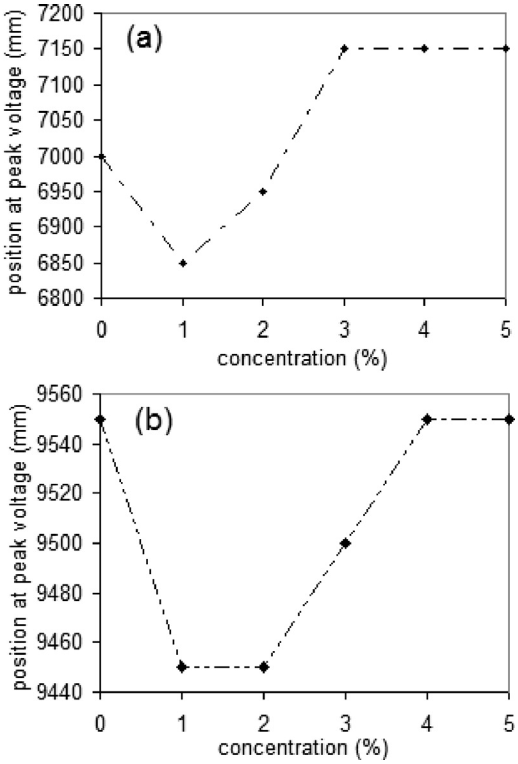


**Fig. 4.** Position at peak voltage versus magnesium ion concentration for (a) CM 1 and (b) CM 2.

ion with concentrations of 1, 2, 3, 4 and 5%. During the experiment, temperature was kept constant to that error due to temperature fluctuation is negligible.

## 4. Result and Discussion

Detection of magnesium ion concentration was obtained by monitoring the output voltage while the displacement between the sensing port and CM is varied. The initial position of the sensing port is about 2 mm above the center of the CM. The curves related to the output voltage as function of displacement sensing port was measured for two different CMs for comparison purpose. The results are analyzed and plotted as shown in Fig. 3. Figs. 3(a) and (b) shows the displacement curves with CM1 and CM2, which has a focal length 6 and 12 mm, respectively. The measurement error for both curves is obtained at around 0.6 mV. It is shown that the peak voltage position was obtained at around 7.0 mm and 9.5 mm for the displacement curves with CM1 and CM2, respectively. It is worthy to note that CM 1 and CM 2 has a diameter of 9.0 mm and 12.0 mm, respectively. In the experiment, the starting position of sensing port was at 2.0 m from surface of concave mirror. Compare to reference of 12, the main novelty of the proposed setup is applying fiber coupler probe as element sensing. In this probe, we have a first peak voltage at very close distance, therefore the sensor is suitable for a shorter distance measurement.

Figs. 4(a) and (b) show the peak voltage position at various magnesium ion concentrations for CM1 and CM2 target respectively. It is shown from both figures that peak voltage position changes irregularly with the variation of magnesium ion concentration. Therefore, it is difficult to predict magnesium ion concentration using the peak voltage position.

Correlation between peak voltage value and magnesium ion concentration is shown in Fig. 5. It indicates a linear trend relation between the peak voltage and magnesium ion concentration. The linearity is more than 99%. Therefore, we can determine value of concentration based on value of peak voltage. Slope of the curve in Fig. 5 defines sensitivity of the sensor, which indicates CM2 produces a better sensitivity than that of CM1. This is attributed to the longer focal length that allows the sensing fiber port to collect more light and increases the sensitivity. The refractive index of various magnesium ion concentrations was also measured using Abbe refractometer and the result is summarized in Fig. 6. The result shows that the refractive index is linearly correlated with the concentration. Therefore, this approach can be used for detection of magnesium ion concentration.

The stability of the sensor was then tested for 720 s for each interval 30 s and the result is presented in Fig. 7. Fig. 7 shows the sensor has a high stability with standard of deviation is 0.4 mV (0.1%) and 0.5 mV (0.11%) for CM 1 and CM 2, respectively. Resolution of the sensor is defined by ratio of standard deviation over sensitivity (slope of the linear curve). Overall, performance of the proposed magnesium ion concentration sensor using fiber cou-

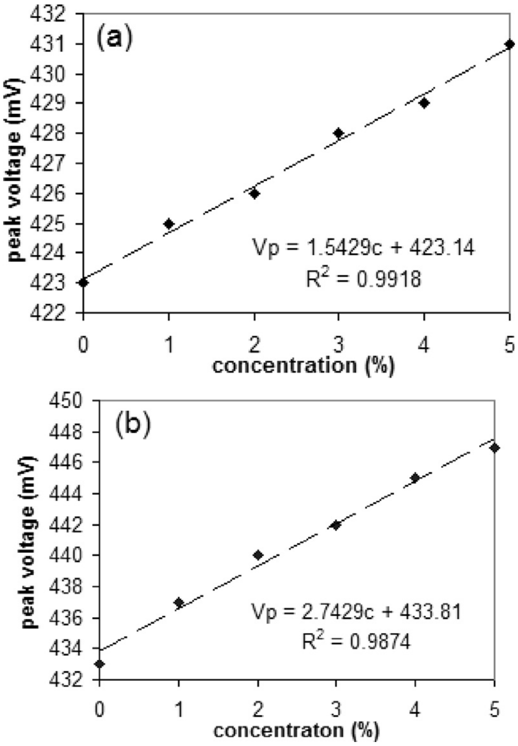


**Fig. 5.** Peak voltage as a function of magnesium ion concentration for (a) CM 1 and (b) CM 2.

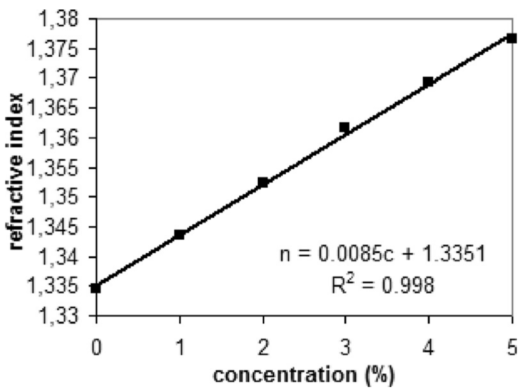


**Fig. 6.** Result of refractive index measurement versus a magnesium ion concentration.

**Table 1**
Performance of the sensor for magnesium ion detection with CM 1 and CM 2.

| Parameters | Value | |
|---|---|---|
| | **CM 1** | **CM 2** |
| Sensor range (%) | 0 – 5 | 0 – 5 |
| Linear region (%) | 0 – 5 | 0 – 5 |
| Sensitivity (mV/%) | 1.54 | 2.75 |
| Resolution (%) | 0.3 | 0.2 |

pler probe for CM 1 and CM 2 is summarized in Table 1. Table 1 shows that sensitivity of the sensor with CM 1 is higher than sensor with CM 2, therefore the sensor resolution with CM 2 is lower than CM 1 (1/1.5 times). The results indicate that fiber coupler based displacement sensor can be used for detection of magnesium ion concentration. During the experiment, the error due to this temperature variation is negligible as the temperature is kept constant at 25°C.

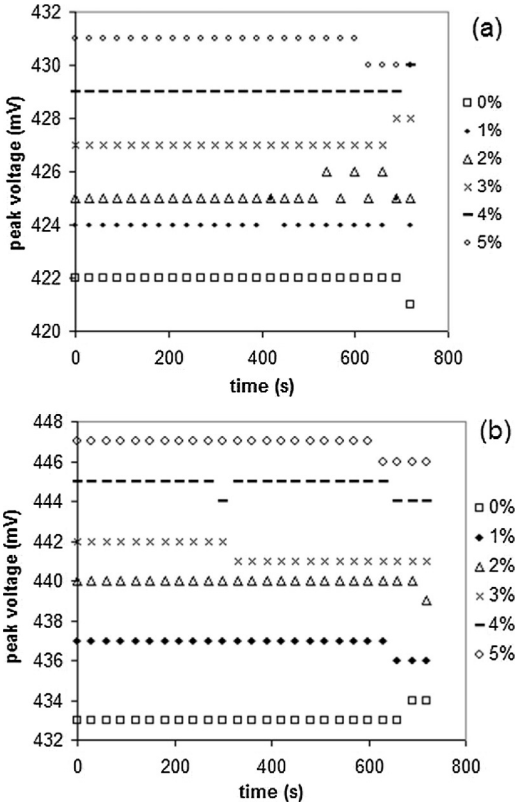


**Fig. 7.** Stability of the sensor for (a) CM 1 and (b) CM 2.

Based on a simple calculation, a response time or bandwidth of optical detector is used in this experiment can be found at 0.175 kHz.

## 5. Conclusion

Fiber optic coupler based displacement sensor configured with CM was proposed and demonstrated for detection of magnesium ion concentration. The results shows that a peak voltage of the sensor is linear to the concentration with the best resolution is obtained at 0.2% and range of 0–5%. The use of CM with a longer focal length improves the sensitivity of the sensor. The simplicity and low cost of the sensor make it suitable for various industrial applications.

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