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Non-contact salinity measurement using a bifurcated fiber bundle sensing

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Abstract. A non-contact salinity sensor using a bifurcated fiber bundle sensing is proposed. The sensor was operated based on intensity modulation due to the variation of displacement between the tip of the probe with the surface of the sample. The light that reflected back into the receiving fiber bundle is analysed and correlation with the salinity of the samples has been performed. This allows the performance of the sensor towards salinity to be quantified based on the front slope, back slope and peak intensity. The proposed configuration has been calibrated and then experimentally validated. The calibration curve can be plotted based on three parameters: peak intensity, front slope and back slope. The peak intensity curve exhibits the highest sensitivity of 1.52×10^{5} a.u./M with the resolution of 4.2×10^{-2} M. The ubiquitousness of sensor configuration and non-contact measurement make the proposed sensor a viable alternative to standard commercial devices.

1. Introduction

Salinity measurement is crucial because it affects the quality of drinking water, marine environment, offshore oil exploration, global climate changes, etc [1]. Due to its importance, salinity measurement has become a research hotspot with the aim of achieving high sensitivity and high precision measurement for various applications. The commonly used technique for salinity detection is by using electrical conductivity principles. There are few disadvantages of this method whereby it is susceptible to electrical interference, not suitable for harsh environment and limited sensitivity. Fiber optics sensors have experienced rapid development, and its implementation in various field of applications have been increased considerably over past decades. The sensors provide non-destructive measurements with high accuracy and high versatility [2]. Due to these advantages, their uses in various situations to detect different biological and chemical parameters of interest has becoming preferable compared to other conventional techniques such as electrical based sensor.

There are many fiber optics sensor techniques for salinity measurement has been proposed and demonstrated. Among the techniques that had been reported are based on optical refraction [3], optical fiber grating (FBG) [4]–[7], long period fiber grating (LPFG) [8], interferometry method [9], [10], surface plasmon resonance method [11] and fiber optics displacement sensor [12]. In the refraction method, the change of refraction angle when light passes through the saline liquid was used to determine the salinity of sample. This method offers high sensitivity salinity measurement with high resolution CCD sensors [13]. However, the complex system setup and large optical probe size of sensor are undesirable for salinity sensing in confined space. Polyamide coated on FBG as a salinity sensitive film was used to simultaneously measure temperature and salinity [5], in the salinity range of 0 % to 7 %, a resolution of 0.028% and a sensitivity of − 0.0358 nm/% able to achieve with this sensor. This FBG salinity sensor is not feasible for long term and portable sensing applications due to its fragility and complexity. Salinity measurement based on interferometry method was reported by measuring interference spectrum shift due to change in refractive index of saline solution [14]. Fiber optics sensor based on surface plasmon resonance (SPR) phenomena involves coating a part of surface of fiber with metallic film with thickness less than 100 nm. SPR effect observed when the evanescent wave passes through the metal film and a shift in the wavelength of light in fiber core occurs as the result. A resolution of 200 ppm achieved in the salinity range of 28 % to 48 % with 50 nm Au SPR coating on an optical fiber [11]. The main disadvantage of SPR sensor is the extremely thin layer of metallic coating is vulnerable to corrosion during immersion in saline solution. Fiber optic displacement sensor (FODS) usually operates based on intensity modulation method that offers simple, reliable and real-time measurements capability [15-16]. In the previous research, immersive type FODS for salinity detection was demonstrated using flat and concave mirrors as the reflector [12].

Most of the salinity sensors mentioned above are contact based where the sensor must be in contact with the saline solution during measurements. The disadvantages of contact-based sensors are the contamination of the samples and corrosion to the sensor probe due to highly ionic nature of the saline solutions. Consequently, these factors adversely affect the purity of the samples and the sensitivity of the sensors. Therefore, a non-contact salinity sensor is needed to preserve the samples and ensure performance of sensor do not degrade over repeated uses. In this paper, a non-contact FODS for salinity sensing is introduced and its performance is evaluated in term of sensitivity, linearity and resolution.

2. Methodology

Figure 1 shows the schematic diagram of the FODS setup used for the salinity sensing in this work. The main components of the sensor were a white light source, a bifurcated fiber bundle, a computer-controlled linear actuator, a spectrometer and a computer. The Dolan Jenner Fiber-Lite A3200 with halogen bulb was used as the light source. The bifurcated fiber bundle was based on glass fibers, which was produced by Autonics Corp. The fiber bundle has 1000 transmitting fibers (TF) and 1000 receiving fibers (RF) where the diameter of each fiber is 50 µm. The fiber bundle cross section is in circular shape where each semicircle consists of TF and RF fibers respectively. An ocean optics USB4000 spectrometer was used in this work to detect the reflected spectrums. The spectral range of spectrometer was 248 nm to 951 nm. The saline solutions were prepared by mixing sodium chloride powder in deionized water and then stirred with magnetic stirrer for 30 minutes. Through this procedure, saline solutions with concentrations of 1.03 M, 2.05 M, 3.08 M, 4.11 M and 5.13 M were prepared.

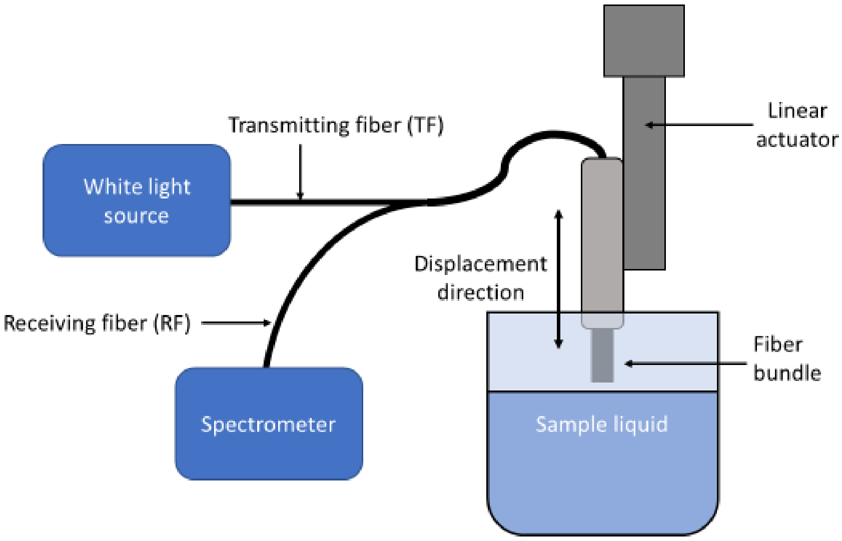

Figure 1: Experimental setup

Output light from the light source was coupled into the TF and the light exited TF from the fiber bundle. Then, the light reflected off the surface of saline solution and part of reflected light entered the RF. The light received by RF was coupled to the spectrometer to detect the spectrum of the received light. The spectrums were collected at various displacements of the fiber bundle from the saline solution surface. The displacement from 10 cm from the surface was done by utilizing a linear actuator where the probe was mounted to the rail of the actuator. The room temperature was maintained at 25 ^{o}C during the measurements.

3. Results and discussion

Figure 2 shows the output spectrum of the white light source. The output light covers approximately from 400 nm to 900 nm with the peak intensity at wavelength of 610 nm. The stability of the light source's output at 610.06 nm also measured for a time period of 60 minutes and it is also shown in figure 2 (b). The light intensity remained stable during the 1-hour period with standard deviation of 0.23 % which is suitable for sensing application.

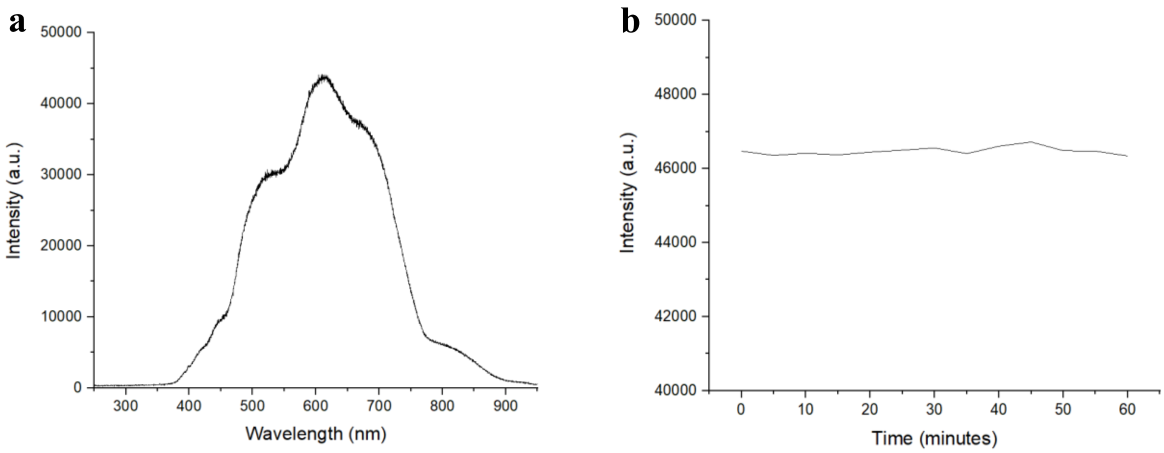

Figure 2: (a) Output spectrum of the white light source and (b) the stability of light source at 610 nm for 60 minutes.

The displacement spectrums recorded at 0 to 10 cm for the sample with salinity of 1.03 M is illustrated in the figure 3. The intensity across the spectrum increases from a minimum value to a maximum intensity when the displacement increases from the zero position. Beyond the maximum intensity position, the intensity decreases gradually for all wavelengths. For salinity sensing application, the sum of intensity from 450 nm to 780 nm was used to discard additional noises below and above the light source output wavelength range. Figure 4 shows the sum of intensity against the displacement graph for the various saline solutions. The general features of displacement curves are front slope, peak intensity and back slope. The front slope region is situated between the zero position and peak intensity position. At zero position, there is negligible overlapping between the reflected light cone from the sample surface and the RF. Therefore, the intensity recorded by the spectrometer is low at the zero position. As the displacement increases, more reflected light enters the RF and the recorded intensity increases till the peak intensity. Displacement beyond the maximum intensity position causes decrease in intensity due to reduction in power density of the light cone according to inverse square law.

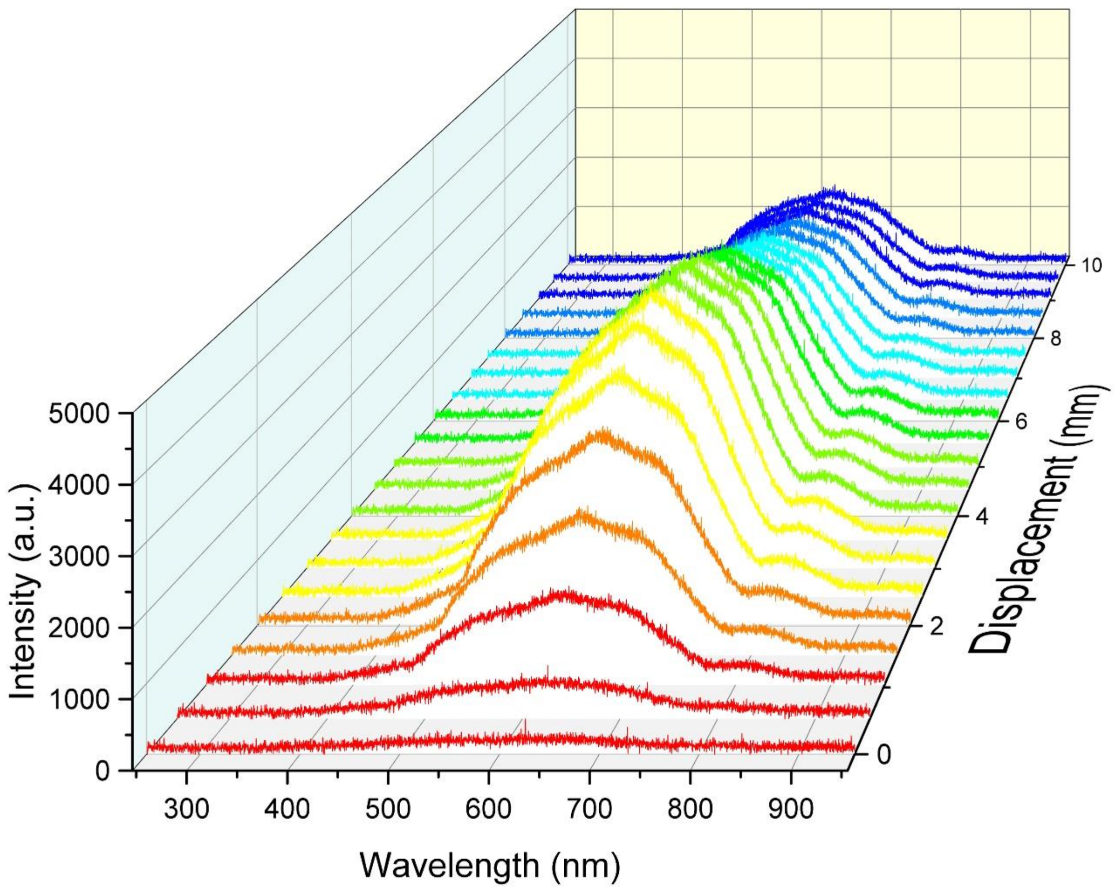

Figure 3: Variation of reflected spectrum with displacement for sample with salinity of 1.03 M.

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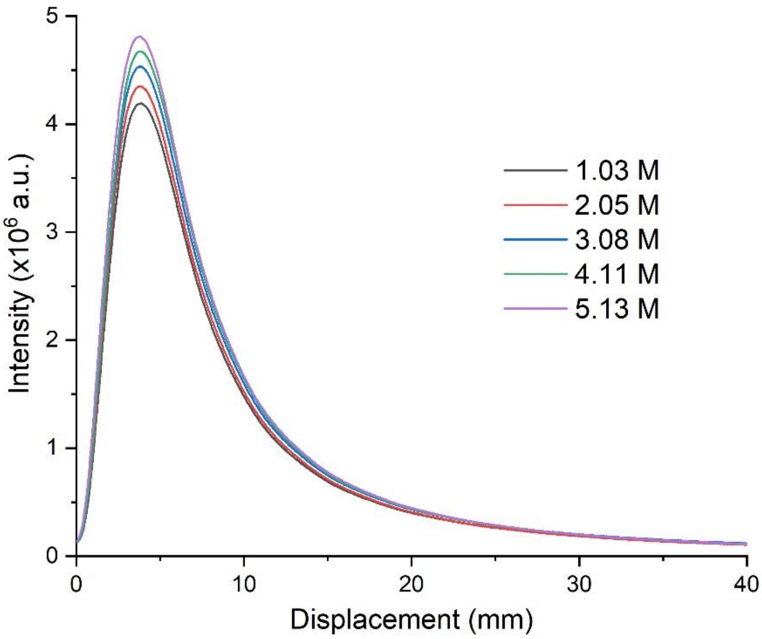

Figure 4: Sum of intensity over displacement for various salinity concentrations

Figure 5 and figure 6 show front and back slope regions of displacement curves with various salinities respectively. The front slope region was taken from displacement range of 1 mm to 2 mm and the back slope was determined from displacement range of 5 mm to 7 mm. The results in figure 5 and figure 6 show highly linear relationships between intensities and displacement where the linear fitting trendlines are also shown in the figures. Therefore, the front slopes and magnitude of back slopes at various salinities were determined and shown in figure 7. In Figure 7 (a), the front slope linearly increases with the salinity. The sensitivity of front slope with salinity is 6.04×10^4 $(\mathrm{a.u./mm})/\mathrm{M}$ with the linearity (R^2) of 0.9903. The molarity resolution of front slope is 5.24×10^{-2} M. The magnitude of back slope also shows linear increment with increase in the molarity. The sensitivity and linearity of the back-slope variation with salinity are 2.32×10^4 $(\mathrm{a.u./mm})/\mathrm{M}$ and 0.9938 respectively. The molarity resolution of the back slope is 6.70×10^{-2} M. Figure 8 shows the variation of peak intensity value with the salinity. The sensitivity of the peak intensity parameter is 1.52×10^5 $\mathrm{a.u./M}$ with highest linearity of 0.9971 compared to front and back slopes linearities. The best resolution among the three sensing parameters was measured with the peak intensity parameter, which is 4.2×10^{-2} M.

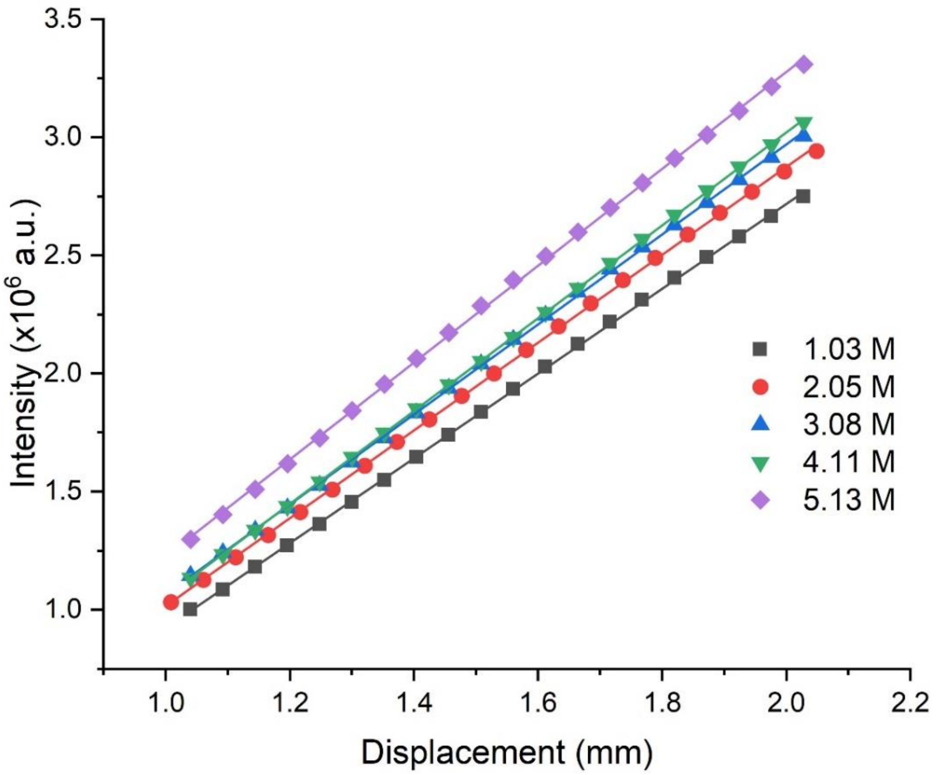

Figure 5: Front slopes of displacement curves with various salinities

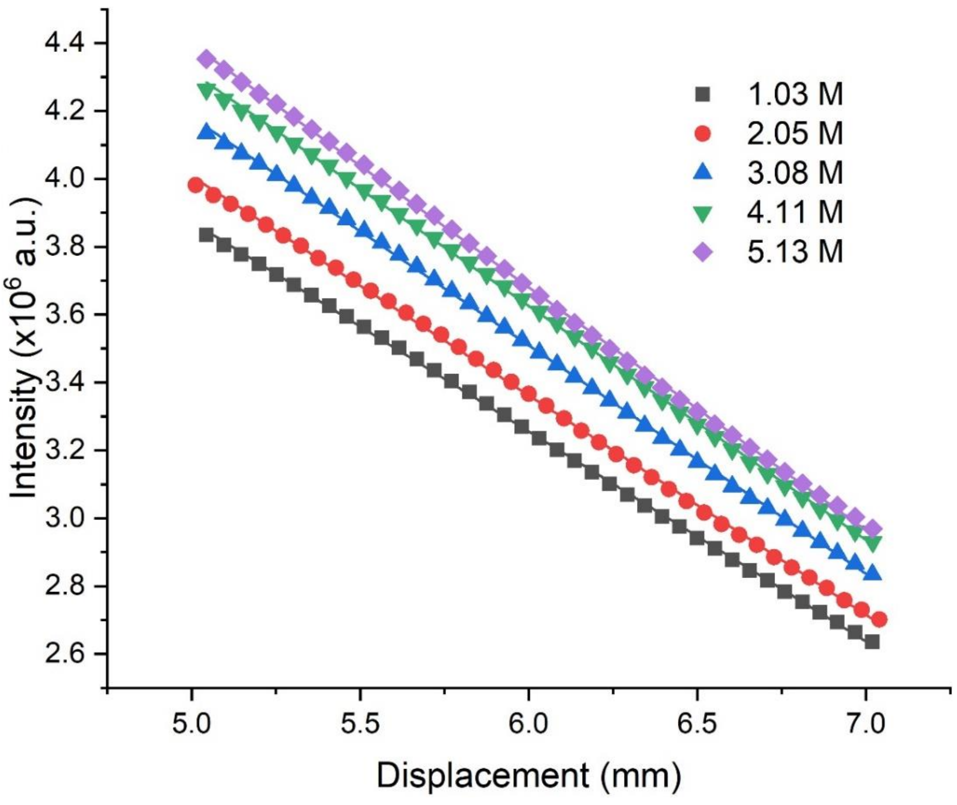

Figure 6: Back slopes of displacement curves with various salinities

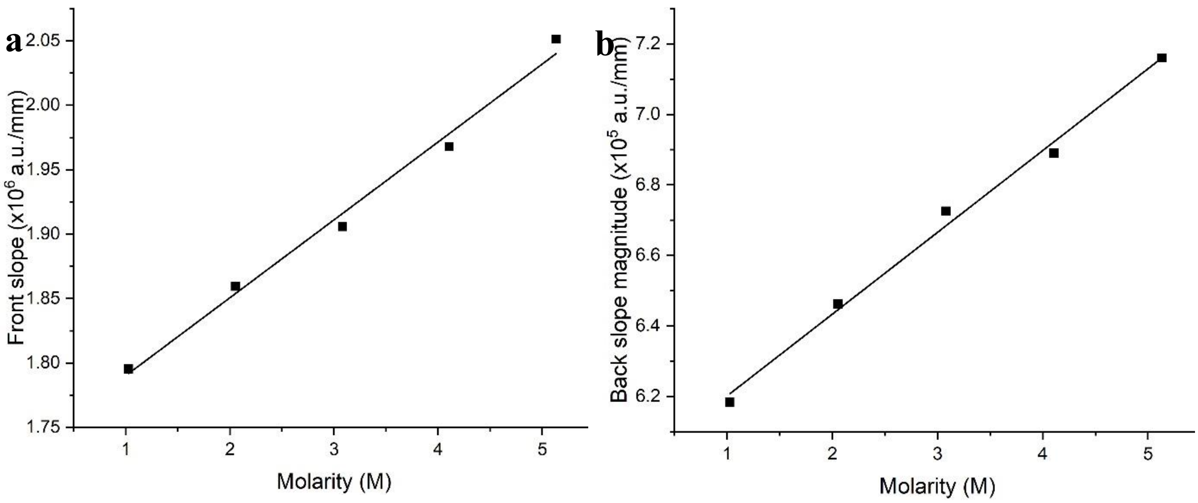

Figure 7: (a) Variation of front slope with salinity and (b) variation of magnitude of back slope with salinity

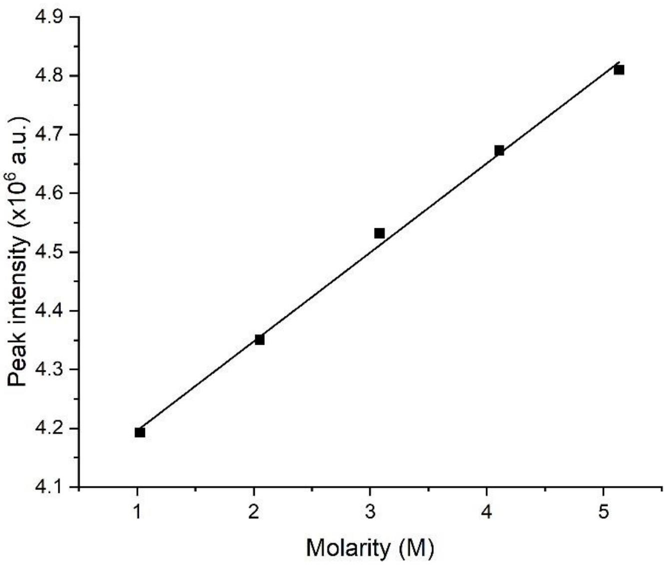

Figure 8: Variation of peak intensity value with the salinity

The sensor performances of the front slope, back slope and peak intensity are listed in the Table 1. The peak intensity showed the best performance parameter for salinity sensing compared to front and back slopes in term of sensitivity, linearity and resolution. This sensor shows superior linearity over wide range of salinities compared to salinity sensors based on polyamide coated FBG and SPR dip-probe technique [5], [11]. The resolution of this sensor can be improved further with high stability light source and addition of vibration-free holder for the samples. Due to non-contact nature of the sensor, the sensor was used repeatedly throughout this study without any sensor probe cleaning, which is not possible with contact-based or immersive type sensor.

Table 1: The sensor performances of front slope, back slope and peak intensity

Parameter	**Sensitivity**	**Linearity**	**Standard Deviation**	**Resolution (M)**
Front slope	$6.04 \times 10^4\ (\frac{\text{a.u}}{\text{mm}})/\text{M}$	0.9903	$3.17 \times 10^3\ (\frac{\text{a.u}}{\text{mm}})$	5.24×10^{-2}
Back slope	$2.32 \times 10^4 (\frac{\text{a.u}}{\text{mm}})/\text{M}$	0.9938	$1.55 \times 10^3\ (\frac{\text{a.u}}{\text{mm}})$	6.70×10^{-2}
Peak Intensity	1.52×10^5 a.u./M	0.9971	6.35×10^3 a.u.	4.2×10^{-2}

4. Conclusion

A non-immersive intensity modulated displacement sensor for salinity sensing is demonstrated by varying the molarity of solution from 1.03 M to 5.13 M. The sensing capabilities of front slope, back slope and peak intensity of displacement curve are evaluated, and the peak intensity is the best parameter for salinity measurement in term of sensitivity, linearity and resolution. The attractiveness of non-contact and contamination free natures of the sensor will be motivating factor for future research efforts to improve the sensor.

5. Acknowledgement

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