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High-Sensitive Seawater Refraction Index Optical Measurement Sensor Based on Position Sensitive Detector

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Abstract: The refractive index of seawater is one of the essential parameters in ocean observation, so it is necessary to achieve high precision seawater refractive index measurement. In this paper, we propose a method for measuring the refractive index of seawater based on a Position Sensitive Detector (PSD). Theoretical model is established to depict the correlation between laser spot displacement and refractive index change, utilizing a combination of position sensitive detector and laser beam deflection principle. Based on this optical measurement method, a seawater refractive index measurement system was established. To effectively enhance the sensitivity of refractive index detection, a focusing lens was incorporated into the optical path of the measuring system, and simulations were conducted to investigate the impact of focal length on refractive index sensitivity. The calibration experiment of the measuring system was performed based on the relationship between refractive index of seawater and underwater pressure (depth). By measuring laser spot displacement at different depths, changes in displacement with respect to both refractive index and depth were determined. Experimental results demonstrate that the system exhibits a sensitivity of 9.9277×10^{-9}RIU (refractive index unit), the refractive index deviation due to stability is calculated as $\pm 7.545 \times 10^{-9}$RIU. Thereby the feasibility of highly sensitive measurement of seawater refractive index is verified.

Keywords: refractive index ; position sensitive detector (PSD); optical measurement; depth

1. Introduction

Ocean parameters such as temperature, salinity, and pressure of seawater are important for the study of marine environment and flow field analysis. The traditional method of detecting the temperature, conductivity, and pressure of seawater using CTD (Conductivity-Temperature-Depth) device. Currently, CTD measure the temperature of seawater with a sensitivity bit of 0.001 °C. However, due to the limitations of the measurement method, CTD device cannot detect the non-ionic substances (SiO_2, CO_2, and soluble organics) in seawater [1,2]. Thus, which leads to deviations in salinity measurement.

Under this circumstance,measuring the refractive index by optical method is an advantageous solution. The refractive index optical measurement is high-sensitive and significance in the analysis of density [3], pressure [4,5], salinity [6,7], temperature [8,9] and environment of the ocean [10]. In 2003, Y. Zhao et al. proposed a optical fiber sensor used for remote monitoring of salinity in water. This sensor is based on the detection of beam deviation due to the refractive index changes of the seawater, and salinity can be measured by a PSD. Salinity measurement with a resolution of 0.012 g kg^{-1}, and the method is applied in a laboratory environment [11]. In 2009, D. Malardé et al. proposed a compact optical refractometer is named as the NOSS to used measuring the refractive index of

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seawater. This refractometer is based on the principle of light refraction, and it is developed using V-block optical structure. The prototype is capable of measuring seawater refractive index with a resolution of 4×10^{-7}RIU, and it has already been applied to the in situ detection of ocean refractive index [12,13]. In 2011, Y. C. Kim et al. developed a sensor of refractive index change based on the combination surface plasmon resonance (SPR). The principle of the surface plasma effect between the evanescent wave on the optical fiber surface and the metal film coating. The type of fiber optic SPR sensor used here has a sensitivity of approximately 1600 nm/RIU and there is a refractive index change of 2×10^{-4}RIU/ppt. With the limit of detection for the smallest shift detectable of the SPR spectrometer employed being 0.04 nm [14]. This method has already been applied to the detection of ocean salinity. In 2016, Y. Hen et al. designed a sensor based on the modulation principle of fiber Bragg grating (FBG) for broad-spectrum light source, calculated the change of refractive index by wavelength bias. The standard deviation of the measured value of refractive index change is 1.46×10^{-4}RIU [15]. In 2018, J. Chen et al. developed a compact refractive index sensor based on total internal reflection (TIR) method with a sampling frequency of 0.1 Hz, and a standard deviation of 4.78×10^{-6}RIU in measuring results is obtained [16]. In 2019, H. Uchida et al. developed a state-of-the-art density sensor for seawater measurements with a sampling frequency of 1.2 Hz based on measuring the refractive index by the interference method. The resolution of the density sensor is 0.00006 kg/m^3 for changing temperature at constant salinity and pressure, 0.00012 kg/m^3 for changing salinity at constant temperature and pressure, and 0.00010 kg/m^3 for changing pressure at constant temperature and salinity. This method is suitable for refractive index measurements on marine samples in a laboratory environment [3]. In 2021, Y. Wang et al. proposed a fiber optic refractive index sensor based on the anti-resonant reflecting optical waveguide and mode interference. The refractive index sensitivity of this sensor is 19014.4 nm/RIU [17]. In 2022, F. Wu et al. design a refractive index sensor based on the dramatic ellipsometric phase change at the long-wavelength band edge in an all-dielectric 1-D PhC. Assisted by the dramatic ellipsometric phase change at the long-wavelength band edge, the minimal resolution of the designed sensor reaches 9.28×10^{-8}RIU. This refractive index measurement method is suitable for monitoring temperature, humidity, pressure, and concentration of biological analytes in a laboratory environment [18]. In 2023, G. Li et al. proposed a seawater salinity sensor array based on a micro/nanofiber Bragg grating (MNFBG) structures, the salinity sensitivity for two cascaded sensor arrays is 8.39 pm/‰ and 7.71 pm/‰, while the temperature sensitivity is 8.28 pm/°C and 8.03 pm/°C. This method is suitable for refractive index measurements on marine samples in a laboratory environment [19].

According to the existing refractive index measurement requirements, the above refractive index optical measurement methods are compared and analyzed. At present, the sensitivity of salinity measurement based on the detection of beam deviation method is 0.012 g kg^{-1}, equivalent to a seawater refractive index about 2.4×10^{-6}RIU. The refractive index sensitivity of the NOSS is 4×10^{-7}RIU. By calculating, the refractive index sensitivity of the sensor of the SPR is 2.5×10^{-5}RIU, and obtained a measurement result with a standard deviation of 8.3×10^{-6}RIU. By calculating, the refractive index sensitivity of the sensor of the FBG about 10^{-4}RIU. The refractive index sensitivity of the sensor of the TIR about 10^{-5}RIU, and obtained a measurement result with a standard deviation of 4.78×10^{-6}RIU. The sensitivity of refractive index measurement based on the interference method is 1.33×10^{-7}RIU, and the standard deviation of the sensor refractive index is 2.93×10^{-8}RIU. The sensitivity of refractive index measurement based on the the anti-resonant reflecting optical waveguide and mode interference about 2.1×10^{-6}RIU. The sensitivity of refractive index measurement based on the dramatic ellipsometric phase change at the long-wavelength band edge in an all-dielectric 1-D PhC is 9.28×10^{-8}RIU. The sensitivity of refractive index measurement based on MNFBG about 10^{-8}RIU.

The refractive index of the ocean varies by 10^{-8} RIU [3]. Thus, the sensitivity of refractive index measurement based on the MNFBG can meet the technical requirements of Marine monitoring, the sensitivity of the other five measurement methods can not meet the accurate measurement of ocean refractive index. However, the MNFBG refractive index measurement methods are relatively easy to achieve refractive index measurement under good laboratory conditions, not suitable for harsh field experimental conditions such as complex oceans.

In this paper, we proposed a method for measuring the refractive index of seawater based on a PSD. Theoretical model is established to depict the correlation between laser spot displacement and refractive index change, utilizing a combination of position sensitive detector and laser beam deflection principle. Based on this optical measurement method, a seawater refractive index measurement system was established. To effectively enhance the sensitivity of refractive index detection, a focusing lens was incorporated into the optical path of the measuring system, and simulations were conducted to investigate the impact of focal length on refractive index sensitivity. The calibration experiment of the measuring system was performed based on the relationship between refractive index of seawater and underwater pressure (depth). By measuring laser spot displacement at different depths, changes in displacement with respect to both refractive index and depth were determined. Experimental results demonstrate that the system exhibits a sensitivity of 9.9277×10^{-9}RIU, the refractive index deviation due to stability is calculated as $\pm 7.545 \times 10^{-9}$RIU. Thereby the feasibility of highly sensitive measurement of seawater refractive index is verified.

2. Structure and Principle of the Refractive Index Optical Measurement System

The optical seawater refractive index measurement adopts the laser beam deviation technique, and its schematic diagram is shown in Figure 1. The light emitted from the laser is passes through the light-incidence window, it reaches the seawater refractive index measurement area. Due to the refractive index gradient of seawater, the laser-seawater interaction caused laser refraction phenomenon. Then, the laser passes through the light-receiving window, the laser is gathered to the spot on the photosensitive surface of the PSD by the focusing lens. Thus, the laser spot position coordinates are obtained from PSD.

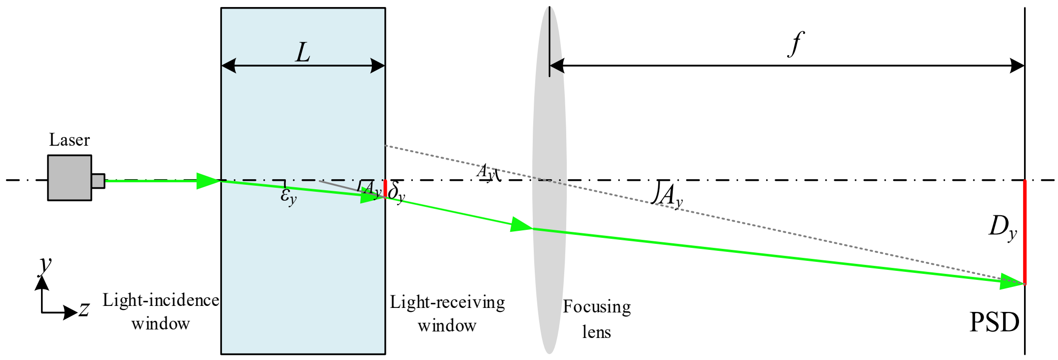

Figure 1. Schematic diagram of seawater refractive index measurement based on the laser beam deviation technique.

The geometric theory of light refraction is an approximation of the physical optics approach. Assuming that the measurement system optical path is a two-dimensional optical path that is isotropic in the x and y directions. Since it is difficult to ensure that the incident laser and the light-receiving window are perfectly perpendicular, the optical path is deflected by the refractive index gradient in the y-direction when the laser enters the measurement zone, so consider only the refractive index gradient in the y direction. The refraction of light caused by the inhomogeneity of light is proportional to the gradient of refractive index in each direction in the y planes. Therefore, the deflection rate of light rays can be expressed as [20]:

$$\frac{\partial^2 y}{\partial z^2} = \frac{1}{n}\frac{\partial n}{\partial y} \tag{1}$$

where n is the refractive index, z is the direction of light propagation, The curvature of the refracted light $\frac{\partial^2 y}{\partial z^2}$ is represented by the gradient of the refractive index $\frac{\partial n}{\partial y}$ of seawater.

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In the refractive index measurement area, the angle of deflection of the light ray in the direction of y axes is obtained by integrating the eq. (1), as follows:

$$\varepsilon_y = \frac{1}{n}\int \frac{\partial n}{\partial y}\partial z \tag{2}$$

where the ε_y is the angle of deflection of the light ray in the direction of y axis, and $\frac{\partial n}{\partial y}$ is the gradient of the refractive index in the y axis direction.

Since the deflection angle is small and the distance between the light-incidence window and the light-receiving window is L, there is the following relationship:

$$\varepsilon_y = \frac{L}{n_0}\frac{\partial n}{\partial y} \approx \tan\varepsilon_y \tag{3}$$

where n_0 is the refractive index of the surrounding seawater.

Therefore, the gradient of the refractive index in the y axis direction is expressed as:

$$\frac{\partial n}{\partial y} = \tan\varepsilon_y \frac{n_0}{L} = \frac{\delta_y n_0}{L^2} \tag{4}$$

where the δ_y is the displacement of the light ray in the direction of y axis.

The relationship between the displacement δ_y generated in the refractive index measurement area and the displacement D_y on the PSD photosensitive surface is shown in Figure 1. If the refractive index measurement zone distance L is short enough, the spot position point on the light-receiving window can be approximated as the corresponding seawater refractive index. The law of refraction is satisfied at the light-receiving window. Therefore, there are:

$$\sin\varepsilon_y = \frac{\delta_y}{\sqrt{\delta_y^2 + L^2}} \tag{5}$$

$$\sin A_y = \frac{D_y}{\sqrt{D_y^2 + f^2}} \tag{6}$$

$$n_1 \sin A_y = \left(n_0 + \delta_y \frac{\partial n}{\partial y}\right)\sin\varepsilon_y \tag{7}$$

where the A_y is the spatial angle from the center of the focusing lens to the spot position on the PSD photosensitive surface in the direction of y axis, the f is the focal length of the focusing lens, and the $\left(n_0 + \delta_y \frac{\partial n}{\partial y}\right)$ is the measured refractive index of the seawater.

Thus, by association equations (4), (5), (6) and (7) are obtained as:

$$\frac{\delta_y(\delta_y^2 + L^2)}{\sqrt{\delta_y^2 + L^2}} = \frac{L^2 D_y}{n_0\sqrt{D_y^2 + f^2}} \tag{8}$$

Substituting Eq. (8) into Eq. (4), it is expressed as:

$$\frac{\partial n}{\partial y} = \frac{D_y}{\sqrt{D_y^2 + f^2}\sqrt{\delta_y^2 + L^2}} \tag{9}$$

Since the focal length f is much larger than D_y and the length of the measuring zone L is much larger than δ_y, there is:

$$\frac{\partial n}{\partial y} = \frac{D_y}{fL} \tag{10}$$

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Similarly, in the direction of x axis $\frac{\partial n}{\partial x}$ can be expressed as:

$$\frac{\partial n}{\partial x} = \frac{D_x}{fL} \tag{11}$$

The relationship between the gradient of the refractive index of the refractive index measurement system and the length of the measurement area L is shown in Figure 2. Considering the sensitivity and compactness of the system, the focal length of the focusing lens of the refractive index system is determined to be $f = 300\text{mm}$ and the sensitivity of the PSD is $D = 10^{-3}\text{mm}$, the length range of the measurement area is set to be $10\text{mm} \le L \le 200\text{mm}$. When $10\text{mm} \le L \le 33\text{mm}$, the sensitivity of the refractive index measurement system is on the order of 10^{-7}RIU. When $33\text{mm} < L \le 200\text{mm}$, the sensitivity of the refractive index measurement system is of the order of 10^{-8}RIU. Considering the sensitivity and stability of the refractive index measurement of the system, the length of the measurement area of the system is determined to be $L = 100\text{mm}$, and the sensitivity of the refractive index measurement of the system is $3.33333 \times 10^{-8}\text{RIU}$.

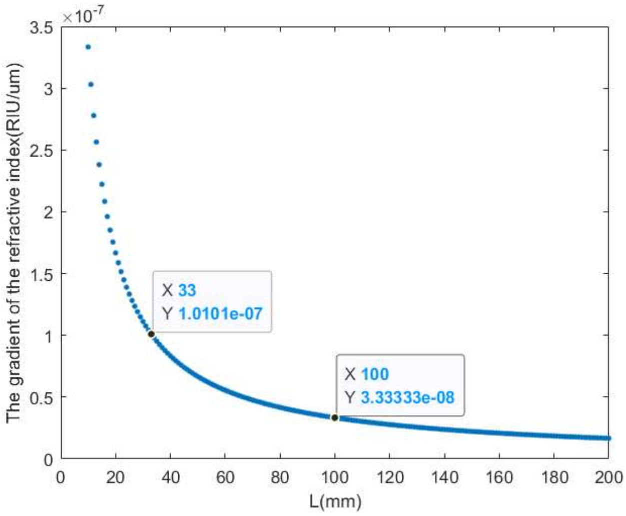

Figure 2. The relationship between the gradient of the refractive index of the refractive index measurement system and the length of the measurement area L.

The relationship between the refractive index change of the refractive index measurement system and the laser spot position change D_y is shown in Figure 3. When the length of the measurement area $L = 100\text{mm}$ and the focal length range of the focusing lens $f = 300\text{mm}$, the laser spot position change $0.001\text{mm} \le D_y \le 4\text{mm}$. The realm of the refractive index change measurement of the system is from $3.33333 \times 10^{-8}\text{RIU}$ to $1.3331 \times 10^{-4}\text{RIU}$.

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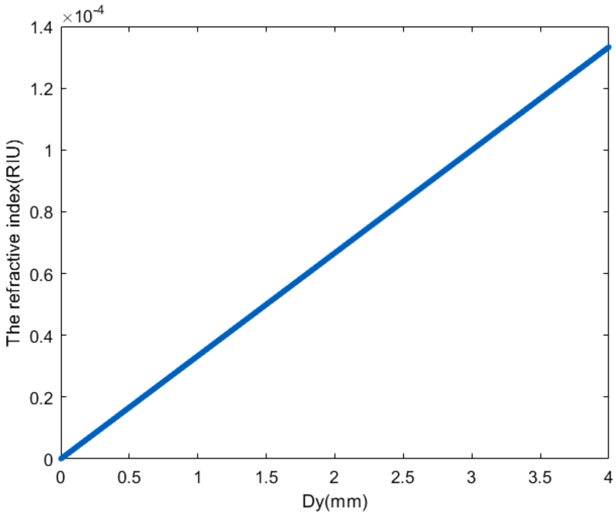

Figure 3. The relationship between the refractive index change of the refractive index measurement system and the laser spot position change D_y.

3. Establishment of the Optical Measurement System and Experimental Results

3.1. Establishment of the Seawater Refractive Index Measurement System

The seawater refractive index optical measurement system based on a PSD, and its optical configuration diagram is shown in Figure 4.

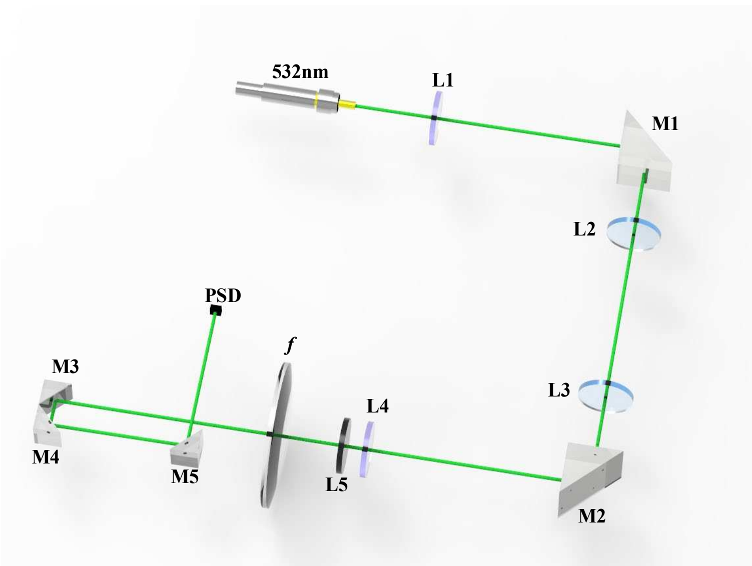

Figure 4. The optical configuration of the seawater refractive index measurement system based on a PSD.

With a view to the absorption and scattering effects in the seawater, the optical system using a green collimated laser with a central wavelength of 532 nm as the measurement light source. After the laser passes through the lens L1, the right-angle prism M1 is used to reflect the incident beam and the light-incidence window L2, it reaches the seawater refractive index detection area. After the laser-seawater interaction caused laser refraction phenomenon, the laser passes through the Light-receiving window L3, the right-angle prism M2, the lens L4. In front of the light-sensitive surface of the PSD, the narrow-band light filter M5 with the same peak wavelength and a bandwidth of 1.1 nm is used to filter out the stray light except for the 532 nm measurement light. The laser is gathered to the spot on the photosensitive surface of the detector by the focusing lens *f*. In order to

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realize the miniaturization of the measurement system structure, a right-angle prism M3, M4, and M5 are added between the focusing lens and the detector photosensitive surface, thereby changing the laser transmission direction. The dimension of the PSD's photosensitive area is $4\text{mm} \times 4\text{mm}$, and the position measurement resolution is approximately 1 μm. Based on the transverse photoelectric effect, the PSD's output signal is independent of the incident light intensity and only related to positions of the incident beam. The seawater refractive index optical measurement system based on a PSD is shown in Figure 5.

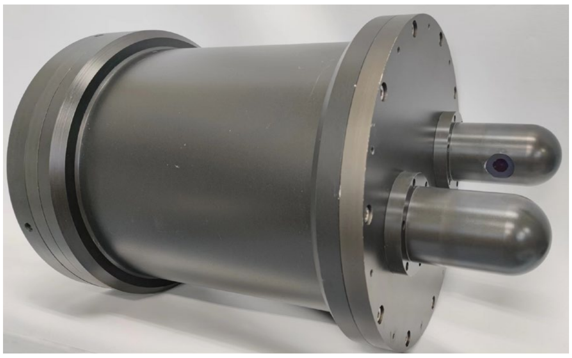

Figure 5. The seawater refractive index optical measurement system based on a PSD.

3.2. Experimental Setup of the calibration experiment

The calibration experiment of the seawater refractive index optical measurement system was carried out in an indoor pool with constant temperature and salinity, and the experimental scenario is shown in Figure 6. The seawater refractive index measurement system is mounted upside down and fixed to the stepper motor, and the refractive index measurement zone was placed about 1.5 m underwater. The seawater refractive index measurement system was immersed in the seawater to be measured for 1 hour to make its temperature the same as the temperature of the seawater to be measured, thus reducing the detection error with temperature. The different laser spot positions on the PSD photosensitive surface corresponding to different depths underwater were obtained by this optical measurement system. The seawater refractive index optical measurement systemare with a sampling frequency of 10 kHz and a sampling time of about 60 s. The seawater refractive index measurement system was rises a distance of about 3 cm. Changing the submerged depth and thus the pressure in the detection area, and data were recorded for about 60 s after each change in underwater depth. The experiment was concluded after recording 30 sets of refractive index measurements.

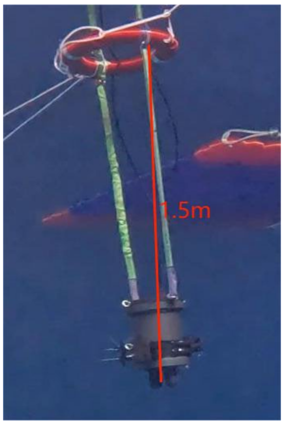

Figure 6. The experimental scenario of the calibration experiment.

3.3. Experimental Results of the calibration experiment

The time domain diagram of the experimental result of the calibration experiment of the seawater refractive index measurement system is shown in Figure 7. According to the experimental results, Since the underwater depth of the seawater refractive index measurement system varies with time and stays at each depth for about 60 s, the time-position line is stepped. The laser spot moves from a position of 0.24277 mm to 0.41671 mm on the PSD photosensitive surface. On average, each depth change corresponds to a laser spot position change of 0.006 mm. Theoretical calculations yielded a 0.006 mm displacement change of the laser spot corresponding to a refractive index change of 1.99998×10^{-7}RIU.

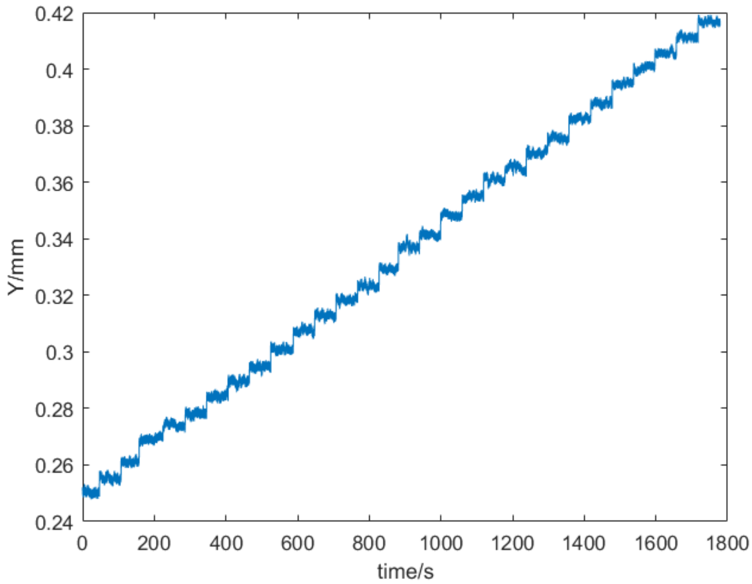

Figure 7. The time domain diagram of the experimental result of the calibration experiment of the seawater refractive index optical measurement system.

According to the experimental results, the laser spot position on the PSD photosensitive surface varies linearly as the measurement system changes depth underwater. The 60 s experimental data obtained from different underwater depth measurements were averaged separately. Linear fitting based on the relationship between underwater depth and pressure being proportional to each other and the variation of refractive index with pressure expressed by TEOS–10 (2010 Thermodynamic Equation of Seawater) [21]. The linear fit plot of depth with spot positions and refractive index with spot positions are shown in Figure 8. Both the underwater depth and the refractive index are linearly correlated with the spot positions and follow the same trend. The fit of the gradient of refractive index of the seawater refractive index optical measurement system is 9.9277×10^{-9} RIU/μm. Since the detection sensitivity of PSD is 1 μm, the sensitivity of the optical measurement system for the refractive index of seawater is 9.9277×10^{-9}RIU. Theoretical calculations yielded a 0.006 mm displacement change of the laser spot corresponding to a refractive index change of 5.95662×10^{-8}RIU. The theoretically calculated value is 3.35758 times the calculated value of the fitted relationship. The experimental results of the calibration of the seawater refractive index measurement system outperform the results of the numerical simulation.

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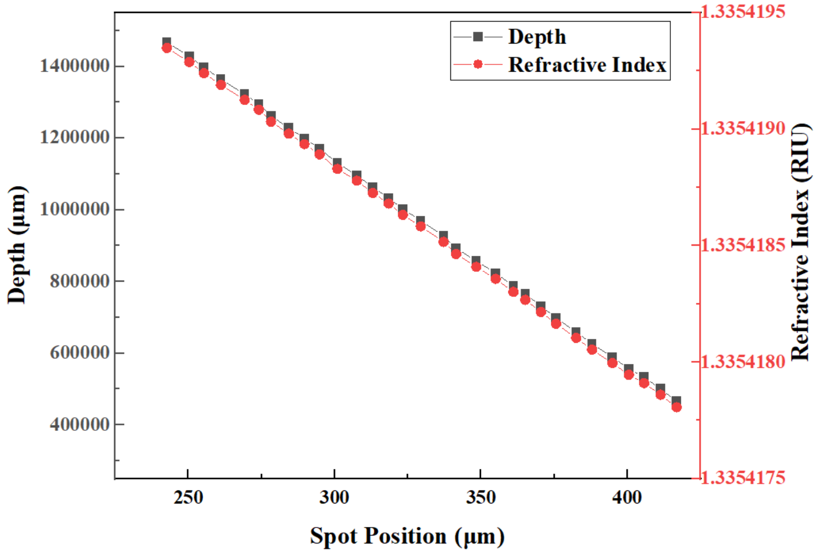

Figure 8. The linear fit plot of depth with spot positions and refractive index with spot positions.

3.4. Experimental Setup of the refractive index measurement experiment

The seawater refractive index measurement experiment with standard salinity seawater was carried out in an indoor glass water cylinder with constant temperature and pressure, and the experimental scenario is shown in Figure 9.

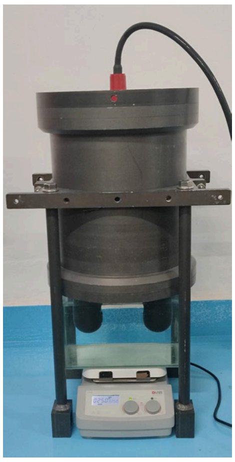

Figure 9. Experimental setup for the standard salinity seawater measurement experiment.

The seawater refractive index measurement system is mounted upside down, and the seawater refractive index detection area was immersed in standard refractive index seawater. The experiments were carried out using standard seawater from the National Centre for Marine Standards and Metrology of China for refractive index measurement experiments. In the experiments, the temperature of the seawater samples was controlled to be 25 °C, the laboratory was a standard atmospheric pressure of 10.1325 dbar, and the ambient humidity was 60%. The refractive index of standard salinity seawater is shown in Table 1.

Table 1. The refractive index of standard salinity seawater.

Salinity (*PUS*)	Temperature (°C)	Pressure (*dbar*)	Humidity	Refractive Index (*RIU*)
20.009	25	10.1325	60%	1.3353862

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3.5. Experimental Results of the refractive index measurement experiment

The seawater refractive index measurement experiment with standard salinity seawater of experimental results is shown in Figure 10. The sampling frequency of the seawater refractive index measurement system is 5kHz, sampling time is about 60 s. The average value of the laser spot position data for this experiment is 3.6014 mm. According to the fitting relationship, when the refractive index of standard salinity seawater is 1.3353862, the position of the laser spot should be 3.603mm. Thus, the laser spot position deviation is 0.0016mm, corresponding to a refractive index deviation of 1.5884327×10^{-8}RIU.

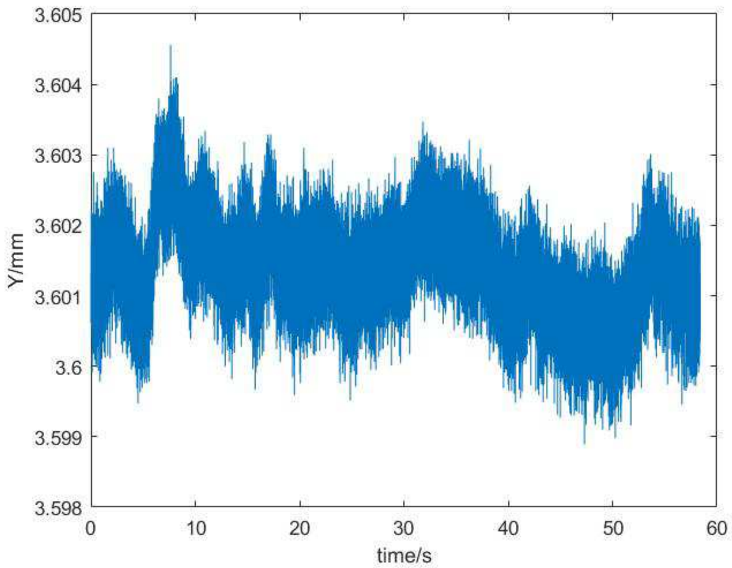

Figure 10. The tability of the seawater refractive index measurement systems.

4. Discussion

The stability of the seawater refractive index measurement system is an important indicator of reliability and reflects the accuracy of the system's measurements. According to the seawater refractive index measurement experiment with standard salinity seawater of experimental results, the jitter signal of the system is ± 0.00176RIU. Based on the measurement sensitivity of the system, the refractive index deviation due to stability is calculated as $\pm 7.545 \times 10^{-9}$RIU. The refractive index deviation of the seawater refractive index measurement system is less than the refractive index measurement sensitivity and within the error range.

5. Conclusions

In this paper, we proposed a method for measuring the refractive index of seawater based on a PSD. Theoretical model is established to depict the correlation between laser spot displacement and refractive index change, utilizing a combination of position sensitive detector and laser beam deflection principle. Based on this optical measurement method, a seawater refractive index measurement system was established. To effectively enhance the sensitivity of refractive index detection, a focusing lens was incorporated into the optical path of the measuring system, and simulations were conducted to investigate the impact of focal length and the length of the measurement area on refractive index sensitivity. Considering the sensitivity and compactness of the system, the length of the measurement area of the system is determined to be L = 100 mm, and the focal length of the focusing lens of the system is determined to be f = 300 mm. The calibration experiment of the measuring system was performed based on the relationship between refractive index of seawater and underwater depth. By measuring laser spot displacement at different depths, changes in displacement with respect to both refractive index and depth were determined. Experimental results demonstrate that the fit of the gradient of refractive index of the seawater refractive index optical measurement system is 9.9277×10^{-9} RIU/μm, and since the detection sensitivity of PSD is 1 μm, the system exhibits a sensitivity of 9.9277×10^{-9}RIU. The stability of the seawater refractive index measurement system was measured by standard salinity seawater refractive index measurement experiments, and the results of the the refractive index deviation due to stability is calculated as $\pm 7.545 \times 10^{-9}$RIU. Thereby the feasibility of highly sensitive measurement of seawater refractive index is verified.

According to various comparisons, the existing seawater refractive index measurement methods do not give satisfactory results for marine refractive index gradient measurements, but the proposed method is proven to be feasible. Furthermore, the proposed seawater refractive index measurement system does not require complex optical structures and can also be used in various applications of underwater vehicle wake measurement besides seawater refractive index measurement, such as motion state monitoring of underwater navigation targets such as AUVs and ROVs.

Author Contributions: Conceptualization, G.Z.; Validation, G.Z.; Formal analysis, G.Z.; Investigation, L.L.; Resources, G.Z.; Writing—original draft, G.Z.; Supervision, X.C. and Y.Z.; Project administration, L.L.; Funding acquisition, Y.Z. All authors have read and agreed to the published version of the manuscript..

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Appendix A

Table A1. The experimental result of the calibration experiment of the seawater refractive index optical measurement system.

Spot Position (*μm*)	Depth (*μm*)	Refractive Index (*RIU*)
242.71	1467100	1.3353193483
250.36	1428000	1.3353192881
255.41	1396700	1.3353192399
261.17	1364100	1.3353191897
269.31	1322100	1.3353191250
274.14	1294900	1.3353190831
278.26	1261500	1.3353190317
284.36	1228300	1.3353189805
289.66	1199000	1.3353189354
294.85	1170660	1.3353188918
300.97	1129800	1.3353188289
307.58	1097000	1.3353187783
313.06	1063000	1.3353187260
318.47	1033400	1.3353186804
323.31	1002100	1.3353186322
329.43	969900	1.3353185826
337.22	926600	1.3353185159
341.46	893100	1.3353184643
348.38	856900	1.3353184086
354.98	823800	1.3353183576
361.09	787100	1.3353183011

365.14	765300	1.3353182675
370.45	731500	1.3353182155
375.6	698600	1.3353181648
382.5	659200	1.3353181041
387.93	626400	1.3353180536
394.88	588900	1.3353179959
400.49	556300	1.3353179457
405.68	533200	1.3353179101
411.3	500700	1.3353178600
416.77	465800	1.3353178063

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