Sensors and Actuators A 233 (2015) 22–25

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Salinity sensing based on microfiber knot resonator

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ARTICLE INFO

Article history:
Received 4 January 2015
Received in revised form 17 June 2015
Accepted 17 June 2015
Available online 25 June 2015

Keywords:
Salinity
Microfiber knot resonator
Sensing
Sensitivity

ABSTRACT

Salinity measurement has become one of the key technologies in marine detection since salinity is an important parameter in oceanography. This paper demonstrates salinity sensing in NaCl solution based on the microfiber knot resonator by estimating its sensitivity from the relationship between the resonance wavelength red-shifts and the increment of salinity. The dependence of sensing sensitivity on microfiber diameter and probing wavelength are also investigated. Results show that sensing sensitivity increase with the decreasing microfiber diameter (3.5 μm–2.5 μm) and the increasing probing wavelength (1500 nm–1650 nm), which are in good agreement with theoretical results. By optimizing our sensing system, the maximum sensitivity is 21.18 pm/‰, which is 16 times higher than that of fiber Bragg grating. Such type of salinity sensor demonstrated here develops a new optical method to measure salinity of liquid and offers useful references for measuring salinity in actual seawater so that ultra-compact optical devices for salinity sensing of ocean can be further developed.

1. Introduction

Salinity, one of the essential parameters in oceanography, plays an important role in marine environment, ocean circulation and other phenomena. As a typical electrode-type device used to measure salinity of seawater, conductivity-temperature-depth (CTD) system has the advantage of high precision. However, this electrical device easily suffers from the electromagnetic interference and is not applicable for salinity measurement on the micro scale due to its large size and complex structure. Moreover, in order to achieve salinity data in certain depth of ocean, series connection of CTDs will have to be used in sea trials, which greatly drives up the costs. Therefore, new miniaturized sensors with low cost need to be developed in order to achieve fine measurement in the ocean.

In recent years, optical methods for salinity sensing have gradually become the focus due to the advantages of electromagnetic immunity, compact size, high sensitivity/precision, low cost and so on [1–7]. For example, Men et al. developed a salinity sensor based on fiber Bragg gratings (FBGs) that presents a sensitivity of 0.0165 nm/M [8]. Frazão et al. used the similar approach to achieve a sensitivity of 1.28 pm/‰ [9]. Another sensor based on polyimide-coated polarization-maintaining photonic crystal fiber (PM-PCF) had a sensitivity of 0.742 nm/M [10]. However, fabricating FBGs and PM-PCF generally require special fibers, polymer coating and expensive equipment for writing and coating. Compared to the above approaches, optical sensors based on microfibers have attracted more and more attention due to their advantages of smaller size, higher sensitivity, faster response, lower cost and simpler fabrication, which have been widely used in physical [11–14] and biochemical sensing fields [15,16]. As a typical structure of microfiber sensor, microfiber knot resonator (MKR) has been proved sensitive to the surroundings and been successfully used in refractive index (RI) [17–19], humidity [20,21], temperature [22,23], magnetic field [24], electric current [25] and UV [26] sensing. Recently, seawater salinity sensing based on microfiber loop resonator has been proposed and modeling on the performance of the salinity sensor has been reported, which proved to be a new optical method to measure seawater salinity with high sensitivity, low detection limit and miniaturized sizes [27]. However, to the best of our knowledge, there is no experimental work so far on the salinity sensing by MKR.

In this paper, MKR-based salinity sensing in NaCl solution is demonstrated experimentally with results showing that the resonance wavelength shifts towards long wavelength linearly with the increment of salinity. Hence, sensing sensitivity can be estimated due to this linear relationship. In addition, the dependence of sensing sensitivity on fiber diameter and probing wavelength are also investigated, which indicate good agreement with theoretical calculations, revealing the availability and reliability of the experiment. By choosing the appropriate parameters for assembling the sensor, the maximum sensitivity measured is about 21.18 pm/‰. The sensor demonstrated here provide a new optical method to

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http://dx.doi.org/10.1016/j.sna.2015.06.019
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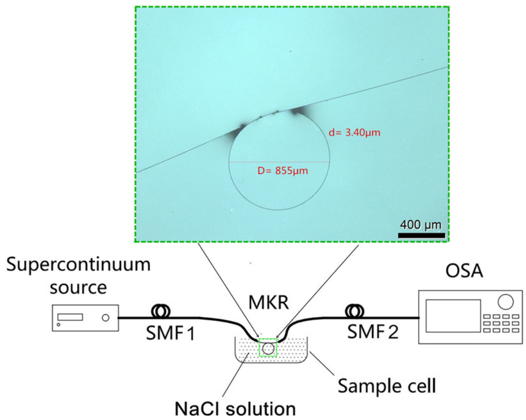

Fig. 1. The schematic diagram of the experimental system. The magnified section shows the details of a MKR with ring diameter of 855 μm and fiber diameter of 3.4 μm.

measure salinity experimentally and offers useful references for measuring salinity in actual seawater, which may have great potential in developing ultra-compact and low cost optical devices used for salinity sensing in the ocean.

2. Experimental

2.1. System and operation

An experimental system is established in order to perform the salinity sensing, as shown in Fig. 1. It consists of a supercontinuum source (*SuperK*^{TM} *Compact*), an optical spectrum analyzer (*Ando AQ6370C*), standard single mode fiber (*Corning SMF-28e*) and a MKR. A broadband light from the supercontinuum source is launched into the MKR via SMF1. The MKR is manufactured from microfiber that is tapered from SMF1 using flame brushing technique. With the help of a fiber probe, the freestanding end of the microfiber is fabricated into a knot under the optical microscope. By pulling the free end of the microfiber with another fiber probe, the MKR with an appropriate size is obtained [28]. The output signal is collected by evanescent coupling from the freestanding end of the MKR to another tapered SMF2 that has been connected to the optical spectrum analyzer (OSA). Finally, the assembled MKR is immersed into the NaCl solution with different salinities. It is known from NASA's global map of ocean salinity that the salinity of vast majority of ocean area ranges between 30‰ and 37‰. The salinity of offshore marine is about 20‰–30‰ or lower. Thus, the measuring salinity scope is chosen to be 20.494‰–37.178‰ and experimentally made by successively adding a certain amount of 20% NaCl solution into 6 ml distilled water. The temperature is measured by a thermocouple thermometer and maintained at 18 degrees Celsius.

An optical microscope image of a typical 855-μm-diameter MKR assembled with 3.4-μm-diameter microfiber is shown in the magnified section of Fig. 1. In order to eliminate the refractive error effect in liquid and estimate the ring diameter more accurately, the MKR is moved to the surface of solution. The shadows in Fig. 1 are caused by the surface tension of liquid.

2.2. Results

By utilizing the above mentioned experimental system and fabrication method, five MKRs are fabricated. Table 1 lists the details of them, including fiber diameters, salinities of samples and the probing wavelengths with data in descending order of fiber diameter. No. 2–5 describe four trials with the same MKR (855-μm ring diameter and 3.4-μm microfiber diameter). Fig. 2 shows the typical

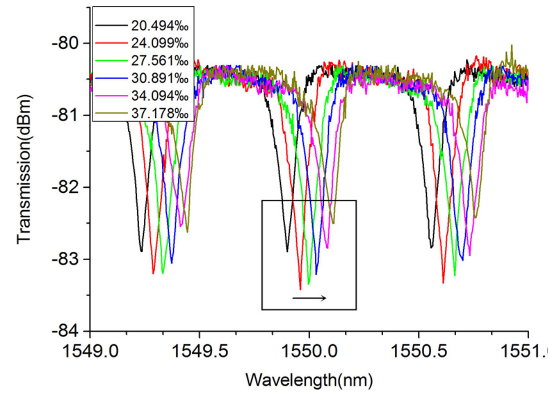

Fig. 2. The transmission spectra of the MKR (No.6 in Table 1) at different salinities.

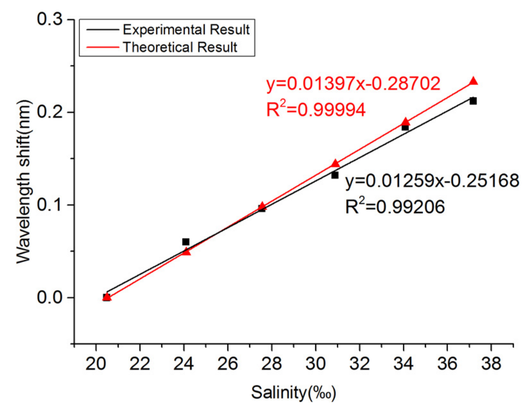

Fig. 3. The experimental and theoretical relationship between resonant wavelength shift and salinity.

transmission spectrum of a MKR (No. 6 in Table 1) with ring diameter of 780 μm and fiber diameter of 3 μm at different salinities. The resonant wavelength shifts towards long wavelength with the increasing salinity, which is caused by the increasing effective RI of waveguide correspondingly. Similarly, the spectra of the other MKRs lead to the same conclusion that the resonant wavelength gets red-shift with the increasing salinity.

3. Analysis and discussion

The red-shift effect of resonant wavelength with the increasing salinity indicates the possibility of realizing salinity sensing by tracking the shift of resonance peak. To estimate the sensing sensitivity, we observe the dependence of a typical resonant peak around 1550 nm on the salinity that is marked in the black rectangle in Fig. 2, and then plot the dependence of resonant wavelength shift on different salinity in Fig. 3. Results show that the wavelength shift increases linearly with the increasing of salinity with a slope of about 12.59 pm/‰, which indicates the measured salinity sensitivity to be 12.59 pm/‰.

To verify the accuracy and reliability of the experiment results, theoretical calculation is performed. Modeling of a MKR immersed in NaCl solution is established. The eigenvalue equation for fundamental mode (HE_{11}) is given by [29]:

$$\left\{\frac{J_1'(U)}{UJ_1(U)}+\frac{K_1'(W)}{WK_1(W)}\right\}\left\{\frac{J_1'(U)}{UJ_1(U)}+\frac{n_2^2K_1'(W)}{n_1^2WK_1(W)}\right\} = \left(\frac{\beta}{kn_1}\right)^2\left(\frac{V}{UW}\right)^4 \quad (1),$$