Salinity Sensor based on a Two-Core Fiber

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Abstract: A highly sensitive salinity sensor based on Two-Core optical fiber is demonstrated for both high- and low-concentration regimes. Salinity of several aqueous solutions is measured in the ranges from 0 to 5 mol/L and from 0 to 1mol/L with sensitivities of 9.60 nm/(mol/L) and 5.85 nm/(mol/L), respectively. The achieved sensitivity is more than 12 and 400 times larger than that recently reported for polymide-coated photonic crystal fibers and polymide-coated fiber Bragg gratings, respectively.

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1. Introduction

Salinity plays an important role in chemical and biological analysis for manufacturing processes and protection of ecosystems. Furthermore, since it is one of the fundamentals parameters of the seawater equation of state along with temperature, salinity sensing becomes essential to climate models and chemical oceanography [1]. Salinity measurement has been traditionally performed based on the electrical conductivity of water due to the presence of chlorine ions [2]. Nevertheless it is clear that this technique presents serious disadvantages such as its susceptibility to electrical interference and the omission of considering non-conductive species affecting seawater density. In this regard, a growing interest on fiber optic sensors has arisen due to their well known superior advantages, such as immunity to external electromagnetic interference, compactness, high sensitivity, and *in situ* measurements.

Fiber optic salinity sensors based on several different techniques can be found in the literature. The more widely studied are those based on fiber gratings [3-5], but there are some other effective proposals such as those based on special fibers [6], displacement and differential measurements [2, 7], interferometry [1], and more recently those based on fiber resonators [8,9]. Despite the fact that sensors based on resonators and differential measurements use simple sensing elements they often require more complex characterization of the resonator/array response and additional signal processing is needed to obtain a correct measurement (i.e. ambiguity treatment, intensity compensation, identification of the center of the light beam, among others). In terms of fiber gratings, it is well known that complex fabrication process is involved and, since they are sensitive to environmental conditions, temperature compensation by using an additional grating is required, which implies double-grating fabrication process. Even if fiber gratings are considered as a viable option, they exhibit low sensitivity, which can be improved, similarly to photonic crystal fibers, by using polymide coatings, but complexity and low cost-effectiveness arise since special equipment is required to coat the fiber. A similar situation occurs for in-fiber interferometers where they exhibit small interaction lengths and high sensitivity, but require special equipment to fabricate the cavities in the fiber.

In this work a simple, compact, and cost-effective fiber optic sensor based on a Two-Core fiber (TCF) is demonstrated. The proposed sensor measures the degree of salinity of the water through the refractive index (RI), which makes it suitable for a wide range of applications. Furthermore, successful operation in both high- and low-concentration regime has been achieved. Salinity of several aqueous solutions is measured in the ranges from 0 to 5 M (M is mol/L) and from 0 to 1 M with sensitivities of 9.60 nm/M and 5.85 nm/M, respectively. The achieved sensitivity is more than 12 and 400 times larger than that recently reported for polymide-coated photonic crystal fibers and polymide-coated fiber Bragg gratings, respectively.

2. Principle of Operation and Experimental Setup

The cross section of the TCF is shown in Fig. 1a. The diameter of the cladding is 125μm and the two cores, with diameter of 8.6μm, are asymmetrically located: one of the cores is located at the center of the fiber while the other is located 15μm away from the central core. Given the separation between the cores, the TCF is basically a directional coupler. Therefore, light coupled into one of the cores will eventually couple into the other core and then back to the first one, and so on, along the length of the TCF. Since one of the cores of the TCF is located at the center of the fiber, it can be easily spliced to standard single mode fiber (SMF). Therefore, when a section of TCF is spliced between two SMF, the expected spectral response is as shown in Fig. 1b. The response exhibits a sinusoidal behavior as a function of wavelength with the peak to peak separation being directly proportional to the TCF length.

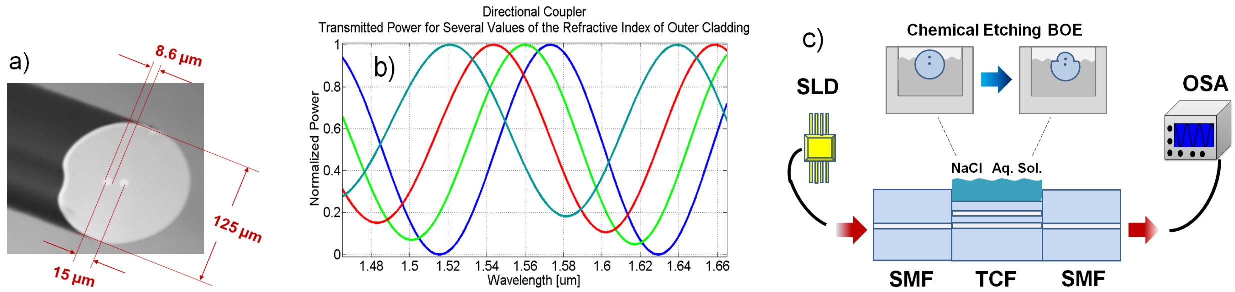

Fig. 1. (a) Cross view of the TCF. (b) Ideal response of the TCF section. (c) Schematic of the TCF RI sensor.

Complete crossover occurs when the guides are phase matched and the interaction length is an exact odd multiple of the coupling length [10]. The coupler response is highly dependent on the coupling coefficient which is also related to the cladding RI. Therefore, if the effective RI of the cladding is modified, then the phase match condition will be achieved at a different wavelength and the coupling process is modified. This is reflected as a shift of the wavelength response of the TCF, and this is the effect that we use to detect RI changes. The proposed TCF RI sensor is schematically shown in Fig. 1c. The sensor consists of a super luminescent diode (SLD), a 50 mm long section of TCF spliced between two single-mode fibers (SMF), and an optical spectrum analyzer (OSA). The interaction length (i.e. 50 mm of TCF) was fixed to the bottom of a channel and carefully aligned to have the external core facing up. The TCF cladding was slowly etched using buffered oxide etchant (BOE), which allows the external core to interact more with the liquid surrounding the TCF. The etching time thus allows us to control the sensitivity of the sensor.

3. Experimental Results

For salinity measurement, several Sodium Chloride (NaCl) aqueous solutions were prepared with concentration ranging from 0 to 5 M (high concentration) and from 0 to 1 M (low concentration). The RI of the solutions exhibit linear dependency with respect to the concentration of the solution for both tested ranges and represent changes in the RI of the solution from 1.3333 to 1.3776 and from 1.333 to 1.3435, respectively [11].

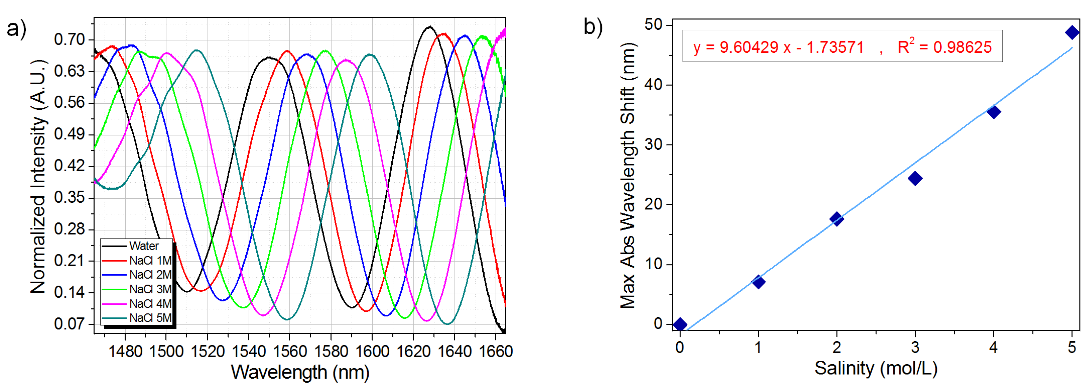

Fig. 2. Response of the TCF salinity sensor in the range from 0 to 5 M. a) Spectral response and b) linear response of the wavelength shift.

As mentioned before, the interaction between the TCF and the surrounding liquid is achieved by exposing the outer core through chemical etching. In this case, the etching time was 293 min. Assuming a constant etching rate of 130 nm/min, the cladding of the outer core is 5 μm-thick approximately. Fig. 2(a) shows the spectral response of the salinity sensor for solutions with concentration ranging from 0 to 5 mol/L. As shown in Fig. 2(b), a total wavelength shift of 48.8 nm is achieved and linear response indicating a sensitivity of 9.60 nm/(mol/L) is obtained, with R^2 equals to 0.98625.

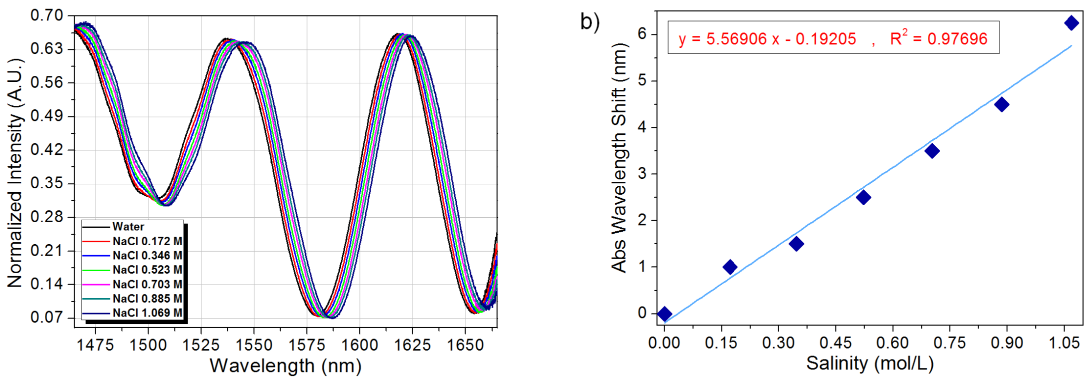

Fig. 3. Response of the TCF salinity sensor in the range from 0 to 1 M. a) Spectral response and b) linear response of the wavelength shift.

On the other hand, considering that the RI of seawater changes from 1.3333 to 1.34 approximately (which is in good agreement with experimental values previously reported), solutions with concentration ranging from 0 to 1.069 mol/L were tested. Fig. 3(a) shows the spectral response of the salinity sensor for these solutions. Despite the wavelength shift decreases due to the smaller RI variation, the sensor response for each solution is clearly identified. As shown in Fig. 3(b), a total wavelength shift of 6.25 nm is achieved and linear response indicating a sensitivity of 5.85 nm/(mol/L) is obtained, with R^2 equals to 0.97696. In both cases, the slight disagreement of the experimental results and the linear response are due to small variations of the solutions. Since the fabrication process is relatively simple and does not require any expensive equipment, the proposed configuration provides a very simple and highly sensible salinity sensor.

4. Conclusion

In summary, a novel, simple, cost-effective, and high sensitive salinity sensor based on a TCF has been demonstrated. Sensitivities of 9.60 nm/(mol/L) and 5.85 nm/(mol/L) for the range from 0 to 5 mol/L and from 0 to 1 mol/L, respectively, were achieved. The achieved sensitivity is more than 12 and 400 times larger than that recently reported for polymide-coated photonic crystal fibers and polymide-coated fiber Bragg gratings, respectively.

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