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Abstract

Test and Analysis of Lateral-Offset Optical Fiber Mach-Zehnder Interferometer Using Near-Infrared Light Employed as Chloride Ion Concentration Sensor †

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Abstract

This paper presents a test and analysis of a lateral-offset optical fiber Mach-Zehnder interferometer (MZI) employed as a chloride ion concentration sensor using a near-infrared light source (amplified spontaneous emission, wavelength = 1520–1620 nm). An 8 cm optical fiber MZI sensor was fabricated and fusion-spliced using a lateral-offset process. We used this 8 cm lateral-offset optical fiber MZI to measure chloride ions in samples of sodium chloride solutions with different weight concentrations ranging from 0.015% to 25% and then analyzed the interference spectra regarding their normalized intensity and wavelength shift and three integral area ranges (1520–1580 nm, 1540–1600 nm, and 1520–1620 nm). The comparative spectral analysis results show that the lateral-offset optical fiber MZI sensor exhibited a linear decrease in its normalized intensity as well as a wavelength shift when the concentration increased. The lateral-offset optical fiber MZI sensor displayed a sine wave plot in the three integral area ranges when the concentration increased. Other than sensing parameters such as the normalized intensity (adjusted R-squared = 0.98223) or wavelength shift (adjusted R-squared = 0.94209), the three integral area ranges (adjusted R-squared = 0.96425, 0.91621, and 0.9577, respectively), which possessed adjusted R-squared values greater than 0.9, are also recommended for use as sensing parameters for the testing and analysis of a lateral-offset optical fiber MZI employed as a chloride ion concentration sensor using a near-infrared light source.

Keywords: fiber-optic sensors; Mach-Zehnder interferometer; chloride ion concentration; normalized intensity; wavelength shift; integral area

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1. Introduction

Mach–Zehnder interferometers are suitable for use in sensing applications since MZI-like sensors offer many advantages, such as a low cost, robustness, low insertion losses, relatively simple fabrication, compactness, ease of use, immunity to electro-magnetic interference, and sensitivity to the chloride ion concentration [1–4].

2. Lateral-Offset Optical Fiber Sensing of Chloride Ion Concentration Using Mach–Zehnder Interferometer

2.1. Fabrication of Lateral-Offset Optical Fiber Mach–Zehnder Interferometer

An 8 cm optical fiber Mach–Zehnder interferometer sensor was fabricated using a piece of single-mode fiber (SMF, Corning SMF-28) through a lateral-offset process [5] employing a fusion splicer (FITEL S178A, see Figure 1a). We used single-mode fiber to make a lateral-offset Mach-Zehnder interferometer for use as a chloride ion concentration sensor able to measure chloride ion concentrations of up to 25%.

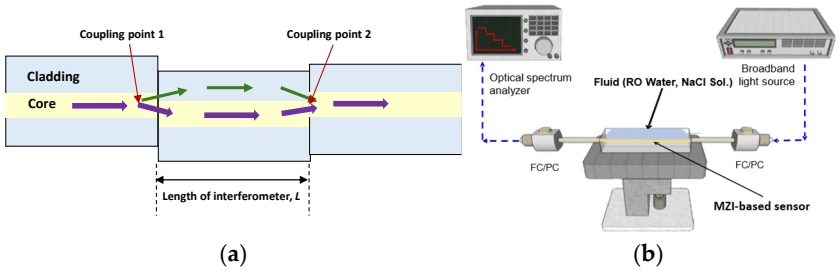


Figure 1. (**a**) Schematic of lateral-offset process for fabrication of Mach-Zehnder interferometer. (**b**) Experimental setup for sensing chloride ion concentration using optical fiber Mach-Zehnder interferometer platform.

2.2. Lateral-Offset Optical Fiber Mach–Zehnder Interferometer for Sensing Chloride Ion Concentration

Figure 1b displays a schematic of the experimental setup for chloride ion concentration measurement with a lateral-offset optical fiber MZI sensor, which was composed of an 8 cm MZI sensor, a near-infrared light source (amplified spontaneous emission, wavelength = 1520–1620 nm), an optical spectrum analyzer (HP 71450B), and a personal computer for data acquisition. Figure 2 shows the transmission spectra captured by the Mach−Zehnder interferometer sensor for samples of sodium chloride solutions with different weight concentrations ranging from 0.015% to 25%.

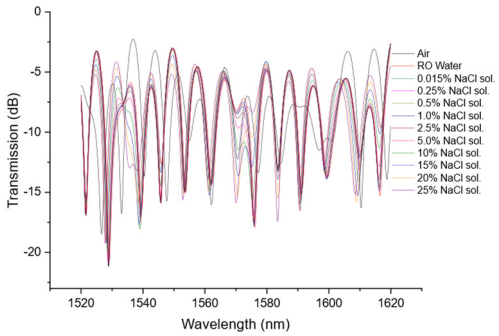


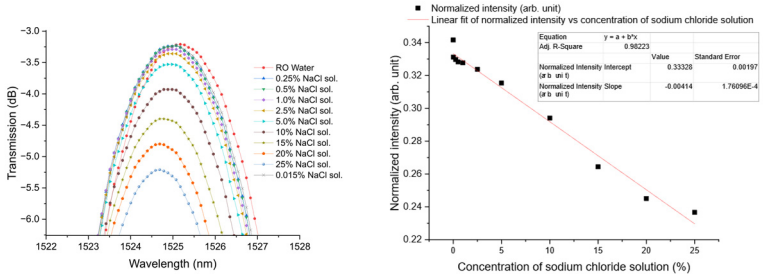
Figure 2. Spectra captured by the Mach–Zehnder interferometer sensor for samples of sodium chloride solutions with different weight concentrations ranging from 0.015% to 25%.

2.3. Comparative Spectral Analysis

For the comparative spectral analysis of the lateral-offset optical fiber Mach−Zehnder interferometer's performance as a chloride ion concentration sensor, we analyzed traditional sensing parameters such as the normalized intensity, as well as the wavelength shift, and proposed three sensing parameters including three integral area ranges (1520–1580 nm, 1540–1600 nm, and 1520–1620 nm). The proposed integral area for each optical spectrum (curve) was integrated, and we calculated the area above the lowest point. We analyzed three integral area ranges (1520–1580 nm, 1540–1600 nm, and 1520–1620 nm) for each optical spectrum.

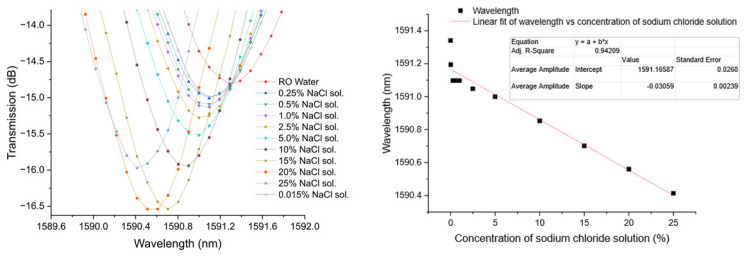
3. Results and Discussion

Figure 3a shows a plot of the chloride ion concentration versus the normalized intensity for samples of sodium chloride solutions with different weight concentrations ranging from 0.015% to 25%, and Figure 3b displays a linear plot of the sodium chloride solution concentration versus the normalized intensity (1526 nm). The results show that the optical fiber MZI sensor exhibited a linear decrease in its normalized intensity when the concentration increased (adjusted R-squared = 0.98223). Figure 4a shows a plot of the chloride ion concentration versus the wavelength shift for samples of sodium chloride solutions with different weight concentrations ranging from 0.015% to 25%, and Figure 4b displays a linear plot of the sodium chloride solution concentration versus the wavelength shift (1590–1592 nm). The results show that the optical fiber MZI sensor exhibited a linear decrease in the wavelength shift when the concentration increased (adjusted R-squared = 0.94209). Figure 5a shows a sine wave plot of the chloride ion concentration versus the integral area (1520–1580 nm) for samples of sodium chloride solutions with different weight concentrations ranging from 0.015% to 25% (adjusted R-squared = 0.96425), Figure 5b displays a sine wave plot of the sodium chloride solution concentration versus the integral area (1540–1600 nm) for samples of sodium chloride solutions with different weight concentrations ranging from 0.015% to 25% (adjusted R-squared = 0.91621), and Figure 5c exhibits a sine wave plot of the sodium chloride solution concentration versus the integral area (1520–1620 nm) for samples of sodium chloride solutions with different weight concentrations ranging from 0.015% to 25% (adjusted R-squared = 0.9577). Thus, those parameters which possessed an adjusted R-squared value greater than 0.9 are recommended for use as sensing parameters, including the normalized intensity (adjusted R-squared = 0.98223) and wavelength shift (adjusted R-squared = 0.94209) as well as the three integral area ranges (adjusted R-squared = 0.96425, 0.91621, and 0.9577, respectively).



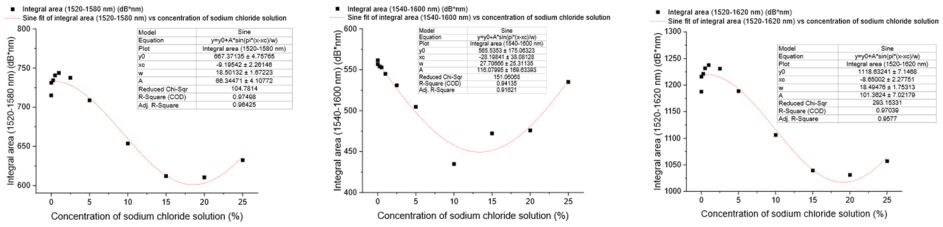
(**a**) (**b**)

Figure 3. (**a**) Plot of the chloride ion concentration versus the normalized intensity obtained using the optical fiber Mach-Zehnder interferometer sensor. (**b**) Linear plot of the sodium chloride solution concentration versus the normalized intensity (1526 nm).



(**a**) (**b**)

Figure 4. (**a**) Plot of the chloride ion concentration versus the wavelength shift obtained using the optical fiber Mach-Zehnder interferometer sensor. (**b**) Linear plot of the sodium chloride solution concentration versus the wavelength shift (1590–1592 nm).



(**a**) (**b**) (**c**)

Figure 5. The optical fiber Mach-Zehnder inter0066erometer sensing results: (**a**) Sine fitting of the chloride ion concentration versus integral areas (1520–1580 nm); (**b**) Sine fitting of the sodium chloride solution concentration versus integral areas (1540–1600 nm); (**c**) Sine fitting of the sodium chloride solution concentration versus integral areas (1520–1620 nm).

4. Conclusions

We have conducted the comparative spectral analysis of a lateral-offset optical fiber Mach-Zehnder interferometer used as a chloride ion concentration sensor by analyzing the normalized intensity, the wavelength shift, and three integral area ranges. The 8 cm lateral-offset optical fiber MZI sensor was fabricated and fusion-spliced using a lateral-offset process. We measured the chloride ions in samples of sodium chloride solutions with different weight concentrations ranging from 0.015% to 25% and analyzed the interference spectra regarding their normalized intensity and wavelength shift and three integral area ranges (1520–1580 nm, 1540–1600 nm, and 1520–1620 nm). The results show that the lateral-offset optical fiber MZI sensor exhibited a linear decrease in the normalized intensity and wavelength shift when the concentration increased. The lateral-offset optical fiber MZI sensor exhibited a sine wave plot in the three integral area ranges when the concentration increased. Other than sensing parameters such as the normalized intensity (adjusted R-squared = 0.98223) or wavelength shift (adjusted R-squared = 0.94209), the three integral ranges (adjusted R-squared = 0.96425, 0.91621, and 0.9577, respectively), which possessed adjusted R-squared values greater than 0.9, are also recommended for use as sensing parameters for the testing and analysis of a lateral-offset optical fiber MZI employed as a chloride ion concentration sensor using a near-infrared light source.

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References

1. Tang, J.L.; Wang, J.N. Measurement of chloride-ion concentration with long-period grating technology. *Smart Mater. Struct.* **2007**, *16*, 665–672. [CrossRef]
2. Wang, J.N. A microfluidic long-period fiber grating sensor platform for chloride ion concentration measurement. *Sensors* **2011**, *11*, 8550–8568. [CrossRef] [PubMed]

3. Wang, J.N.; Tang, J.L. Photonic crystal fiber Mach-Zehnder interferometer for refractive index sensing. *Sensors* **2012**, *12*, 2983–2995. [CrossRef] [PubMed]
4. Villatoro, J.; Minkovich, V.P.; Pruneri, V.; Badenes, G. Simple all-microstructured-optical-fiber interferometer built via fusion splicing. *Opt. Express* **2007**, *15*, 1491–1496. [CrossRef] [PubMed]
5. Bianchetti, M.; Avila-Garcia, M.S.; Mata-Chavez, R.I.; Sierra-Hernandez, J.M.; Zendejas-Andrade, L.A.; Jauregui-Vazquez, D.; Estudillo-Ayala, J.M.; Rojas-Laguna, R. Symmetric and Asymmetric Core-Offset Mach-Zehnder Interferometer Torsion Sensors. *IEEE Photonics Technol. Lett.* **2017**, *29*, 1521–1524. [CrossRef]

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