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Research Article

Fiber-Optic Aqueous Dipping Sensor Based on Coaxial-Michelson Modal Interferometers

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Fiber-optic modal interferometers with a coaxial-Michelson configuration can be used to monitor aqueous solutions by simple dipping of few centimeters of a fiber tip. The fabrication of these sensors to work around 850 nm enables the use of compact, robust, and low-cost optical spectrum analyzers. The use of this type of portable sensor system to monitor sewage treatment plants is shown.

1. Introduction

Since long period gratings (LPGs) were proposed for sensor applications [1]; one can find a significant number of publications where the temperature and strain response of LPG are investigated. Here, we are particularly interested in chemical sensor applications [2], more specifically in refractive index measurements of aqueous solutions. The use of a matched pair of LPG defining an in-line modal interferometer with a coaxial-Mach-Zehnder configuration has been investigated [3] for temperature and strain measurements [4] as well as for chemical applications [5]; this interferometric structure exhibits an enhanced sensitivity to the physical and chemical properties of the surrounding media.

At present, we are specifically interested in the coaxial-Michelson configuration, where a single LPG and a short section of fiber, with its end properly cleaved and coated with a metal, define a compact modal interferometer. This type of interferometer was, first, investigated as a temperature sensor, [6] and, later, refractometric applications have been reported in the 1400–1600 nm wavelength range [7, 8]. The multiplexing of this sensors using low-coherence reflectometry has been also demonstrated [9]. Among the characteristics of this configuration, which is well suited to monitor aqueous solutions using portable sensor systems, we can point out the robustness of the interferometer and the fact that the measurement can be easily performed dipping the fiber tip into the liquid.

Our work is focused on the preparation of LPG-based coaxial-Michelson interferometers at ∼850 nm, instead of the 1400–1600 wavelength range, in order to enable the use of compact and low-cost optical spectrum analyzers to extract the information of the sensor. This approach permits easy multiplexing of several sensors if it is required. In addition to the calibration of the sensor response, we demonstrate the application of this type of sensor to monitor sewage treatment plants.

2. Sensor Fabrication and Experimental Arrangement

The LPG is photoinscripted in a hydrogen-loaded germanosilicate fiber using a continuous wave UV laser at 244 nm. The fiber is single mode at 850 nm and has a step index profile, 0.15 numerical aperture, 4 μm core diameter, and 125 μm cladding diameter. The use of a point-by-point writing technique provides a rather flexible choice of the cladding mode to which the core mode is coupled, since the period can be adjusted precisely. Several LPGs with a period of 313 nm have been fabricated. Figure 1(c) shows the transmission spectrum of one of these LPGs in air, that is, when the fiber is stripped and surrounded by air. The spectra of the LPGs were monitored during the fabrication process, and the depths of the resonances centered at 820 nm and 850 nm were adjusted to be about 3 dB by controlling the length of the grating (7.3 mm). Thus, about a 50% of the power entering the LPG is coupled to the cladding modes LP_{05} and LP_{06} at the resonances of 820 and 850 nm respectively, while the rest of the power remains in the fundamental core mode of the fiber.

Once one LPG is written, the fiber is cleaved at a certain distance L from the end of the LPG (7 cm in our case) and the front surface of the fibers coated with a gold layer by evaporation in a vacuum chamber. In this way, compact and robust coaxial-Michelson interferometers are obtained. Figure 1(a) gives a schematic diagram of the experimental arrangement and a detail of the interferometer. The sensor head is defined by the 7 cm long interferometer, plus the length of the LPG, and the interrogation is carried out by a compact optical spectrum analyzer (OSA) and a superluminescent light emitting diode (SLD); the optical spectrum of the SLD is depicted in Figure 1(b). The OSA that was used in our experiments is manufactured by Ocean Optics (HR4000) and has a resolution of 80 pm and weights 1 kg.

3. Experimental Results and Discussion

Figure 2(a) gives the spectra corresponding to several interferometric fringes within the range 853–870 nm, while Figure 2(b) gives the detail of the fringe centered at 863.5 nm. We can observe in Figure 2 the wavelength shift produced when the sensor head is immersed in water solutions with different concentration of glucose (mass %). The spectrum of the sensor in air is also included. In this example, relatively large concentrations of glucose were used. Measuring the shift of, for example, the interferometric fringe centered at 863.5 nm, one can calibrate the response of the sensor. In fact, one can calibrate the sensor response either in terms of the wavelength shifts of a given fringe or in terms of intensity variations at a given wavelength. Both alternatives are illustrated in Figure 3 for the case of the spectra recorded in Figure 2.

The refractive index of a glucose solution increases about 1.6×10^{-4} per unit of mass % [8]. Thus, the wavelength shifts reported in Figure 2 correspond to refractive index increase of 8×10^{-2}. The optical resolution of the OSA would permit to reach a detection limit of 5%, that corresponds to a refractive index change of 8×10^{-4}. Similar results were obtained with the different sensor heads that were prepared, all with a length $L = 7$ cm. If it is necessary, the detection limit can be improved significantly by coating the fiber with a thin film of a material with higher refractive index than the cladding [10]. The length of the sensor head can be increased, as well, to increase the detection limit. However, any small temperature change might deteriorate dramatically

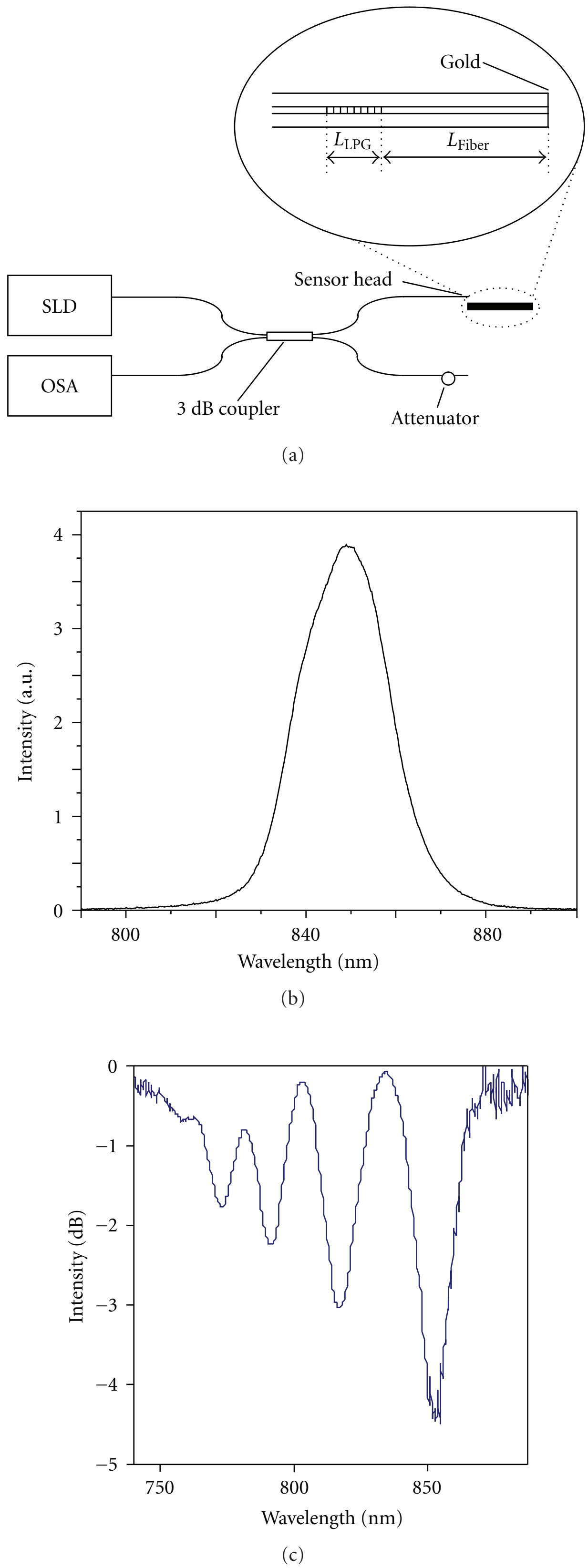

Figure 1: (a) Schematic diagram of the sensor system with a detail of the sensor head. (b) Spectrum of the SLD. (c) Spectrum of one LPG.

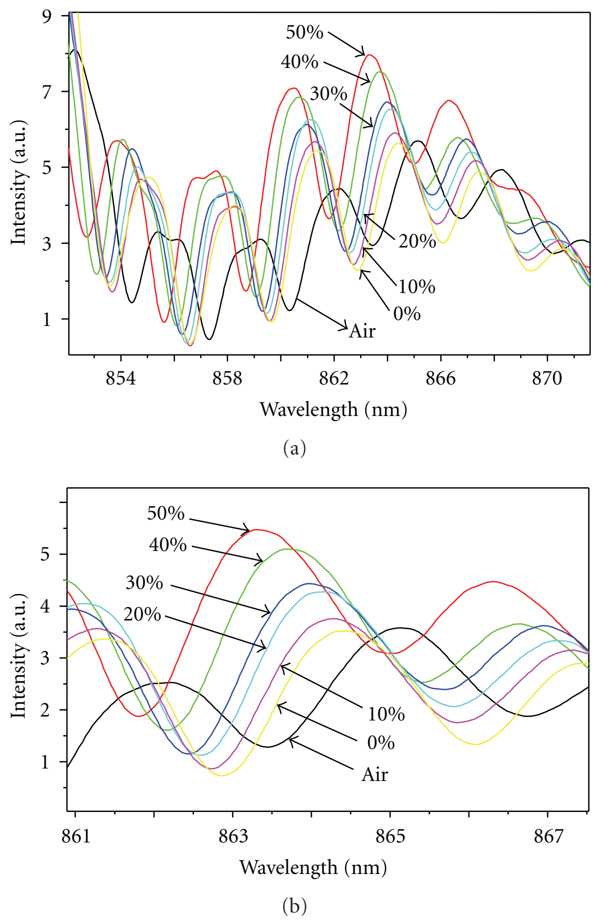

FIGURE 2: (a) Spectra of several interferometric fringes produced by the sensor head for different glucose concentration (mass %) and when the sensor is in air. (b) Detail of the spectra of the interferometric fringe centered at 863.5 nm.

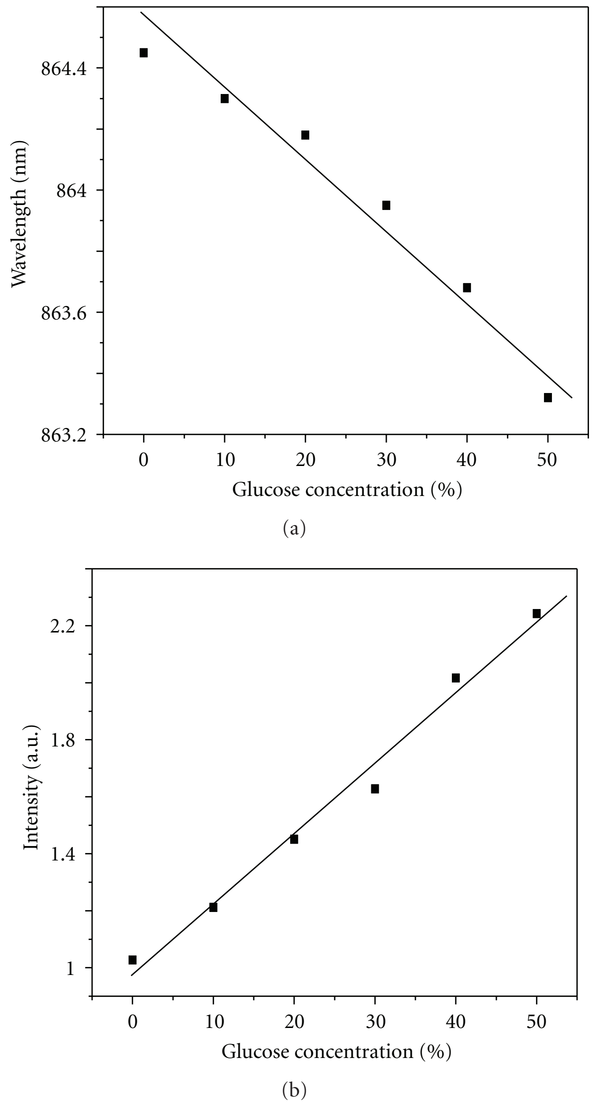

FIGURE 3: (a) Wavelength shift of the fringe centered at 863.5 nm as a function of the glucose concentration (mass %). (b) Intensity reflected by the sensor head at 863.62 nm as a function of the glucose concentration (mass %).

the detection limit, since, in addition to the temperature drift of the LPG and the interferometer itself, the thermo-optic coefficient of water is relatively high (-8×10^{-5} $^{\circ}C^{-1}$). Thus, the use of a reference solution, at thermal equilibrium with the samples to be measured, might be essential to insure the reliability of the measurements in a practical application.

One interesting feature of this type of sensor heads is that the measurement does not rely on the transmission of an optical beam through the solution. This advantage can be exploited to develop chemical sensors for cloudy solutions, as it is the case of sewage. In order to illustrate this application we present in Figure 4 the spectra of the fringe centered at 860.5 nm for 4 different samples of sewage. These samples were taken at the entrance of a sewage treatment plant at different times over one day. All four samples produced a wavelength shift of 750 pm with respect to pure water, which corresponds to a refractive index change of 5×10^{-2}. The four samples were filtered to remove particles in suspension and were measured again. No important changes were observed within the resolution of the sensor heads. The inset of Figure 4 gives the spectra of the same interferometric fringe for the four samples of water after removing the suspended particles.

4. Conclusion

Using single mode fiber at 850 nm, compact and robust coaxial-Michelson modal interferometers have been prepared using a long period grating as an equivalent 3 dB beam splitter. Direct dipping of the sensor head in water solutions permits the measure of small refractive index changes, and, working at 850 nm, low-cost, high-sensitivity, and portable optical spectrum analyzers can be used to interrogate the sensor. The sensor system that has been described here can be used to monitor sewage treatment plants, since the presence of particle in suspension does not deteriorate the response of the sensor.

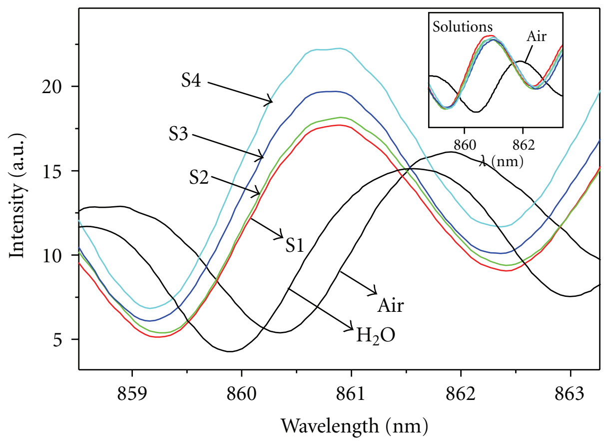

Figure 4: Spectra of the interferometric fringe centered at 860.5 nm for air, water, and 4 samples of sewage. The inset gives the fringes after filtering the samples to remove the suspended particles.

Acknowledgments

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