

Investigations on sensitivity of long period gratings modified by gold nanoparticles

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Abstract:

A simple and effective method is proposed to improve spectral sensitivity and detection limit of long period gratings for refractive index or chemical sensing, where the grating surface is modified by colloidal gold nanoparticles.

Introduction

Recently, long period fiber gratings (LPGs) have been demonstrated as excellent refractive index (RI) sensors for chemical and biochemical sensing. At the same time, there has been an increasing interest in applying the extraordinarily optical properties (e.g., absorbance and resonance wavelength) of noble metal colloidal nanoparticles such as Au or Ag, due to their potential applications for chemical and biological sensing. A number of nanoscale biosensors and chemosensors have been realized through shifts in the localized surface plasmon resonance (LSPR) extinction maximum of gold or silver nanoparticles [1-5]. The wavelength shifts are mainly caused by adsorbate-induced local refractive index changes at the surfaces of nanoparticles. Among the LSPR sensors, we have recently demonstrated an optical fiber biosensor that exploits the LSPR of self-assembled Au colloids (SAGC) on the grating portion of a long period fiber grating (termed CM_{Au}LPG) [6]. The attenuated total reflection spectrum of SAGC is sensitive to the refractive index of its surrounding medium, which can be used for monitoring the solution bulk and for label-free detection of antigen/antibody binding at the surface of the Au colloids.

Taking sucrose solution and sodium chloride solution as examples, this paper will present the significant enhancement of sensitivity and limit of detection for chemical solution concentration sensing using an LPG sensor with its cladding surface modified by gold nanoparticles.

Principle of Refractive Index Sensing

An LPG is a photo-induced periodic modulation of RI along the core of a single-mode fiber, with a typical index perturbation of 10^{-4} , grating periods between 100 μm -1 mm and length of 2-5 cm. The LPG couples light from a guided fundamental core mode LP₀₁ to different forward-propagating cladding modes HE_{1m} in an optical fiber. The coupling of the light into the cladding region generates series of resonant bands

centered at wavelength λ_m in the transmission spectrum, since a cladding mode is rapidly attenuated in the fiber due to the scattering losses. The center wavelengths λ_m of an attenuation band are solutions of the following phase matched conditions: [7]

$$\lambda_m = [\bar{n}_{core}^{01} - \bar{n}_{cladding}^{1m}] \Lambda \quad (1)$$

where \bar{n}_{core}^{01} is the effective refractive index of the fundamental core mode at the wavelength of λ_m , which is also dependent on the core refractive index and cladding refractive index. Also $\bar{n}_{cladding}^{1m}$ is the effective refractive index of the m th cladding mode at the wavelength λ_m , which is also a function of cladding refractive index and the refractive index of the surrounding medium. Λ is the period of grating. When the concentration or the refractive index of the surrounding medium changes, also $\bar{n}_{cladding}^{1m}$ changes and a wavelength shift can be obtained. The wavelength shift can be linearly related to the concentrations of the solution under test. LPG can be very sensitive to the changes in temperature and deformations by fiber imperfections and bending. Therefore, temperature changes and strain effects must be compensated or avoided.

Experimental

The LPGs studied in this work were fabricated in Furakawa SM-332 hydrogen-loaded fibers, utilizing an amplitude technique with a pulsed 193nm ArF excimer laser (laser energy of $\sim 135 \text{ mJ/cm}^2$ and total exposure time of ~ 3 minutes) operating at 10Hz. The fiber was hydrogen loaded at a pressure of 120 bar over a period of two weeks at room temperature. The length of the LPG was 2.3 cm long and the grating period was about 550 μm long. After the laser exposure, all the LPGs were annealed at 150 $^\circ\text{C}$ for 24 h to stabilize their transmission spectrum. The preparation of Au colloids can be found in Ref. [2] and the production of colloidal Au-modified LPGs (CM_{Au}LPG) was followed by the procedure as reported in Ref. [6]. The fiber-optic sensing system used to measure the transmission spectrum of the sensor is also adopted from Ref. [6]. In this work, a number of LPGs and CM_{Au}LPGs sensors associated with various attenuation bands were measured and investigated.

Results and Discussion

For all LPGs used in this work the strain sensitivity were found to be very small ($0.09 \pm 0.01 \text{ pm}/\mu\epsilon$) and exhibited nearly insensitive to strain changes. The sensitivity of the LPG sensors to temperature was about $0.05 \pm 0.02 \text{ nm}/^\circ\text{C}$. We kept sample solution at the same temperature (within 0.1°C). Therefore, the results reported here were not influenced by temperature and strain effects. To characterize the LPG or CM_{Au} LPG as a concentration sensor, measurements with sucrose and sodium chloride aqueous solutions were performed. The surrounding RI was controlled through the use of sucrose solutions with various concentrations [6]. The experiment used to measure refractive index sensitivity was followed by Ref. [8]. Our results for both solutions show that both LPG and CM_{Au} LPG sensors exhibited a linear decrease in the transmission loss and resonance wavelength shift when the concentration increased, demonstrating that LPG and CM_{Au} LPG are suitable for chemical sensing.

By comparison, when a LPG and a CM_{Au} LPG was used to measure the concentration of a sucrose solution, our results show that RI sensitivity of LPG sensor in term of refractive index increased from $-33 \pm 1.0 \text{ nm}/\text{RI}$ to $-36 \pm 1.0 \text{ nm}/\text{RI}$ in the range of 1.34-1.41, as shown in Fig. 1 and Fig. 2, respectively. Combined with the sensitivity analysis of transmission loss peak this leads to a RI resolution of 8.6×10^{-3} and 2.92×10^{-4} , respectively. The measured response of sodium chloride solutions by weight concentration from 0% to 20%, with and without the modification of colloidal gold nanoparticles, indicated that the sensitivity increased from $-0.05 \pm 0.01 \text{ (nm/\%)}$ to $-0.07 \pm 0.01 \text{ (nm/\%)}$, respectively. When conducting the same performance tests, experimental results showed that the accuracy of concentration measurement with this gold-coated LPG sensor was better than $0.2 \pm 0.1 \%$ by weight and limit of detection can be improved from $0.04 \pm 0.01 \%$ to $0.02 \pm 0.01 \%$. The limit of detection of 0.0001% by weight can easily be achieved if an optical spectrum analyzer with spectral resolution of 0.1 pm is used. Therefore, results presented in this paper demonstrated that gold nanospheres modified on the fiber grating could increase its sensitivity in detecting solution concentrations significantly.

Conclusion

In this paper, we have demonstrated an optical fiber sensor based on anomalous reflection of self-assembled Au colloids on the grating portion of an LPG that can significantly enhance the sensitivity and detection limit for chemical solutions. This type of sensor has potential applications in medical diagnostics, biochemical sensing, and environmental monitoring. The advantage

of this type of the sensor is relatively simple of construction, small, light, robust, low-cost, and ease of use. Moreover, the sensor has the potential capability for on-site, in vivo, and remote sensing, and has the potential use for disposable sensors.

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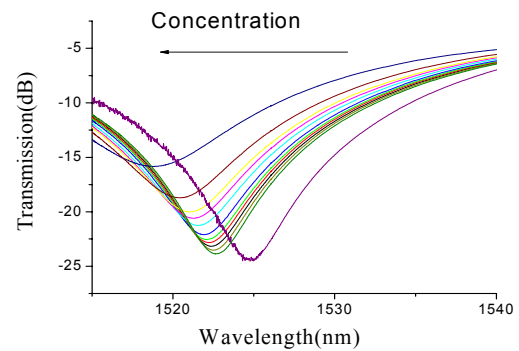


Fig. 1. The wavelength shift of a bare LPG sensor in sucrose aqueous solution with increasing weight concentration.

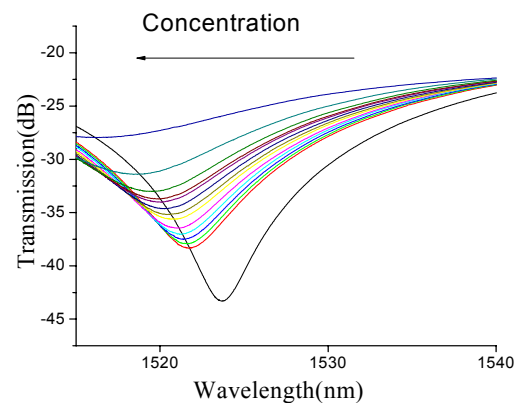


Fig. 2. The wavelength shift of a gold-coated LPG sensor with increasing concentration of sucrose in aqueous solution.