Sensors and Actuators A 229 (2015) 8–14

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

A super continuum characterized high-precision SPR fiber optic sensor for refractometry

Hamid Esmaeilzadeh[a,b], Ezatollah Arzi[a,*], François Légaré[b], Maxime Rivard[b], Alireza Hassani[b]

[a] Department of Physics, University of Tehran, North Kargar Street, Tehran, Iran
[b] Institut National de la Recherché Scientifique, INRS-EMT, Varennes, Québec, Canada

ARTICLE INFO

Article history:
Received 24 September 2014
Received in revised form 11 March 2015
Accepted 11 March 2015
Available online 18 March 2015

Keywords:
D-Shaped fiber
Side-polished fiber optic sensor
Surface plasmon resonance
Refractometry
SNR
Plasmonic sensors

ABSTRACT

Here we introduce a high sensitive side-polished fiber optic based surface plasmon resonance (SPR) sensor for refractometry in liquids for 1.32–1.37 Refractive Index Unit (RIU). In fabrication, a Controllable Hybrid Polishing Method (CHPM) was used to make high quality D-shaped fibers. For characterization, a super continuum (SC) light source was used in the measurement setup. The sensor has a spectral sensitivity of 5200 nm/RIU with a *Limit of Detection* (LOD) of 5.8×10^{-6} RIU. Also, we have demonstrated that by reducing the intensity noise in our light source, a *Signal-to-Noise Ratio* (SNR) of 12.6 dB and a *Limit of Detection* (LOD) of 3.7×10^{-6} RIU is achievable in an intensiometric approach.

1. Introduction

Due to the advantages of immunity to electromagnetic interference and being non-stimulant in explosive or flammable environment, having high sensitivity and long distance remote measurement capability, side-polished fiber optic sensors have received a great deal of attentions in an extensive range of sensing applications including liquid refractometry [1], gas [2], temperature [3], biochemical and biosensing [4–7], and also in other fiber based devices such as directional couplers [8], polarizers [9,10], and telecom filters [11] during recent decades. Monitoring Liquid Refractive Index (LRI) change plays a major role in chemical and biosensing applications and because of that it has been done using Surface Plasmon Resonance (SPR) optical fibers [12,13]. Despite of all previously done researches, there is still a room for practical improvement of these types of sensors. Here, our main goal is to achieve higher sensitivity, and better *Limit of Detection* (LOD), in D-shaped optical fiber based SPR sensor operating for LRI changes from 1.32 to 1.37.

In the fabrication part, the most important task is to delicately remove the clad of a fiber optic to reach the evanescence waves of a propagating light. We have used a Controllable Hybrid Polishing Method (CHPM) for clad removing of standard single-mode optical fibers.

In the characterization of the fabricated LRI sensors, reducing the errors in the measurement system is crucial to get a better precision. One of the significant errors in an optical measurement system is the noise of the light source. Among the various types of the noises for a light beam, the noise of its intensity, or optical power fluctuations, is more important in an intensiometric approach, because it restricts the measurement precision through decreasing the signal-to-noise ratio (SNR) of the fiber optic sensor. In our case we need to have a stable broadband light beam which is due to be launched into the core of the optical fiber sensor, as narrow as 10–60 μm, using an optical coupling setup.

The commercial broadband light sources which have been used traditionally in similar fiber optic sensors are halogen-tungsten lamps, and rarely white light LEDs, integrated with an optical coupling system leading to a fiber optic outlet. In these commercial light sources, manufacturing efforts to make a low noise production is restricted by economic factors, such as marketing competition,

* Corresponding author at: Head of Nanophysics Research Laboratory, Department of Physics, University of Tehran, Kargar Shomali Street, 1439955961 Tehran, Iran. Tel.: +98 21 61118619; fax: +98 21 88004781.
E-mail address: arzi@ut.ac.ir (E. Arzi).

http://dx.doi.org/10.1016/j.sna.2015.03.021
0924-4247/

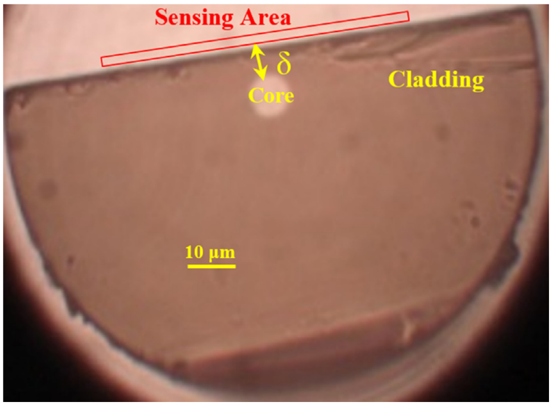

Fig. 1. An optical microscopic image of the cross-section of the side-polished standard single-mode fiber optic showing the residual cladding δ and the sensing area on the polished surface.

to reduce the price. Hence, one must try to provide a broadband light source with higher stability, or less intensity noise. Therefore, we employed a super continuum (SC) broadband light source in the measurement setup to generate a low noise and high power beam, through illuminating a photonic crystal fiber by a stabilized ultrafast pulsed laser. In the following sections, we first describe the fabrication process of the sensor and then demonstrate the characterization process of our fabricated sensor, and finally present the results obtained.

2. Fabrication

Our device works based on the excitation of surface plasmons in a thin layer of gold, coated on a side-polished fiber optic (8/125 μm), by evanescence waves of guided mode in the fiber. The performance of such plasmonic LRI sensor strongly depends on two factors, the residual cladding thickness δ [14], shown in Fig. 1, and also to the smoothness of the polished surface in sensing area, because of its influence on the quality of the coated metal layer [15]. Fig. 1 shows a sample of our side-polished fibers which was fabricated by the CHPM technique, introduced in our previous work [16], benefits from the advantages of both mechanical polishing and chemical etching methods.

In mechanical polishing, only one side of the fiber is removed and the other side remains untouched, unlike chemical etching in which the fiber clad is removed from all sides, resulting in higher mechanical strength for the fragile fiber. On the other hand, chemical etching can gradually remove cladding of the fiber whereby enables us to reach a desired residual cladding thickness (δ), with a precision of 100 nm. Hence, the combination of these two methods in the CHPM technique improves the mechanical stability of the polished fiber optic and accomplishes a good smoothness for the side-polished surface with a roughness of 3.9 nm, measured by Atomic Force Microscopy (AFM).

In order to use SPR mechanism, we need to deposit a thin gold layer on the fabricated side-polished optical fiber. For this purpose, a gold layer having a thickness of 45 nm was coated on the surface of the side-polished area by DC sputtering deposition method at room temperature, with a deposition rate of 0.3 Å/s, a plasma power of 5 W and a vacuum pressure of 1.2×10^{-6} Torr.

3. Measurements and results

3.1. Optical setup to characterize the sensor

In order to test and characterize the fabricated devices, it is necessary to arrange an optical setup which mainly includes a broadband light source, the fabricated sensor adjacent to an analyte, and an optical detector, schematically shown in Fig. 2a. As mentioned before, we chose super continuum light source in the measurement setup. The mechanism of the SC beam generation is based on nonlinear optics effects for which when the ultra-short pulses pass through a crystal as a nonlinear medium, the bandwidth broadening is occurred for them. Fig. 2b shows the setup we used for the SC beam generation in which an ultrashort pulsed laser beam (from an Ar^+-pumped mode-locked Ti:sapphire laser) after passing through several optical pieces is launched into a commercial microstructure optical fiber (SC-800, NKT-Photonic, core diameter of 2 μm and length of 12 cm) and finally becomes a relevant broadband SC beam in visible-near IR range.

In order to have a high stable SC light source beam, it is necessary to minimize all kinds of noise sources (e.g., perturbations caused by sound or mechanical vibration, thermal noise, dark current noise, excess laser noise) whereby reaching to the lowest possible level of intensity noise, that is, *shot noise limit*. Shot noise is a quantum noise effect, related to the discrete nature of photons leading to a fundamental randomness of photon flux that is transformed into fluctuations in the photocurrent upon photodetection [17]. In another word, the fundamental limit to the optical intensity noise, as observed in many situations such as photodiodes or CCD cameras, is given by shot noise.

Before following the shot noise reduction, we give a definition for optical noise here. There are actually various features of noise for a light source; such as: amplitude or intensity noise, phase noise, and timing noise. In the context of intensity noise of a light source, it is common to specify the *Relative Intensity Noise* (RIN), which is the power noise normalized to the average power level. The optical power of the laser can be considered as $P(t) = P_{av} + \delta P(t)$ with an offset power of P_{av} and a fluctuating quantity $\delta P(t)$ with zero mean value. The RIN is then given by δP divided by the average power. Nevertheless, a root mean square (RMS) value of RIN is usually more useful, hence RIN can also be statistically described as follows [18]:

$$\mathrm{RIN} = \left.\frac{\delta P(t)}{P_{av}}\right|_{\mathrm{RMS}} = \frac{\sqrt{\langle \delta P^2 \rangle}}{P_{av}} = \sqrt{\int_{f_1}^{f_2} S(f)\mathrm{d}f} = \sqrt{\langle S \rangle \Delta f} \quad (1)$$

where $S(f)$ is Power Spectral Density (PSD) noise, due to amplified spontaneous emission, $\langle S \rangle$ is the mean PSD noise, and f_1 and f_2 are the noise frequency boundaries in the detection bandwidth interval (Δf). In the shot noise limit which the RIN is limited only by the shot noise, it is given by [19]:

$$\mathrm{RIN}_{shot} = \frac{\langle S \rangle}{P_{av}} \quad (2)$$

in which the PSD is independent of noise frequency (*white noise*), and then RIN of the laser decreases with increasing average optical power P_{av}, as demonstrated by Obarski and Hale [20]. It implies that having a high power pulsed laser can help to reduce the shot noise of the laser beam.

On the other hand, the noise of the SC beam generally depends on wavelength, pulse energy, chirp or duration, and repetition rate of the pulsed laser [21–23]. Nevertheless, the studies done by Newbury et al. [21] on the generated SC beam in the microstructure fiber, shows the resulting noise of the SC beam mainly arises from the shot noise of the input laser pulses implying the importance of the shot noise reduction. Considering the above mentioned cases, the optimized parameters of the pulsed laser that we chose to reach the minimum RIN, were 12 nJ, 850 nm, 55 fs and 80 MHz for pulse energy, wavelength, pulse duration, and repetition rate respectively.

Fig. 3 shows an ultra-short optical pulse train acquired using a high-speed photodiode detector (DET36A – Si Detector, Thorlabs) and then displayed by a digital oscilloscope (TDS1001b, Tektronix)