Optical cavity coupled surface plasmon resonance sensing for enhanced sensitivity

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A surface plasmon resonance (SPR) sensing system based on the optical cavity enhanced detection technique is experimentally demonstrated. A fiber-optic laser cavity is built with a SPR sensor inside. By measuring the laser output power when the cavity is biased near the threshold point, the sensitivity, defined as the dependence of the output optical intensity on the sample variations, can be increased by about one order of magnitude compared to that of the SPR sensor alone under the intensity interrogation scheme. This could facilitate ultra-high sensitivity SPR biosensing applications. Further system miniaturization is possible by using integrated optical components and waveguide SPR sensors.

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Surface plasmon resonance (SPR) has become one of the most important label-free biological and chemical sensing techniques because of its relatively high sensitivity and reliability[1−4]. The surface plasmon wave (SPW) in the thin metal layer can only be excited when the wave vector of the incident light at a certain wavelength matches the wave vector of the SPW. Tiny changes in the properties of the material in contact with the metal layer can be detected by measuring changes in the SPR effects. Various high-sensitivity[5], multi-analyte[6], or portable[7] SPR sensors and systems have been studied to realize detections of biochemical interactions[8] and/or the existence of biological substances[9]. Sensitivity is a key parameter for any biosensing techniques and for SPR sensing, it is defined as the derivative of the monitored SPR parameter, such as SPR resonant wavelength, angle, or intensity, with respect to the refractive index of the sample under test[10]. In order to detect biological interactions under very low concentrations or affinities, even higher sensitivity than the current level is demanded and a number of schemes based on improved sensor structures or optical systems have been proposed and studied[11−14].

Cavity enhanced sensing techniques have become an attractive alternative in various optical sensing applications, where the loss variations from the optical sensors can be 'amplified' by the optical feedback in the laser cavity. When the laser is biased near its threshold, small changes in the cavity gain or loss can result in large output power jumps. This can be used to yield much larger optical sensing signals in a variety of applications[15−17].

We propose and realize a SPR sensing system based on the cavity enhanced technique. The SPR sensor is put inside a fiber-optic laser cavity. The sensitivity, given by the dependence of the output optical intensity on the sample variations, can be increased by about one order of magnitude compared to that of a traditional intensity-interrogation SPR system.

In contrast to the previous multi-pass SPR sensitivity-enhancing schemes based on a passive cavity[13], the intra-cavity dynamics in an active cavity can provide much larger sensitivity enhancement[15]. Here the SPR sensor is used as a loss sensor, which is tuned to a fixed angle close to the SPR angle for the laser's lasing wavelength. This is similar to the traditional intensity interrogation scheme, where the loss due to the SPR sensor changes nearly linearly with the refractive index of the sample so that the measurement in the output power from the sensor directly correlates with the refractive index variations. When the SPR sensor is inserted into the laser cavity, the loss caused by the SPR sensor at the lasing wavelength affects the balance of gain and loss within the optical cavity and thus affects the output power of laser significantly. The effect is much more dramatic when the cavity is biased near the threshold point. Large change of the output power resulting from a relatively small variation of the loss from the SPR sensor provides the 'amplification' of sensitivity when compared with the traditional interrogation scheme.

In our experimental setup, as shown in Fig. 1, a ring fiber laser is built with a SPR sensor in the cavity. A 980-nm distributed feedback (DFB) laser is used as the pump source and its bias current needs to be accurately controlled in the resolution of 0.1 mA. The pump light is coupled into an 11-m-long piece of erbium-doped fiber

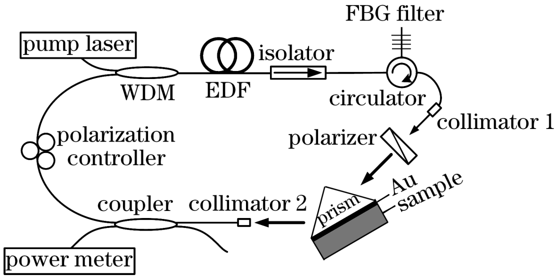

Fig. 1. Experimental setup of optical cavity coupled SPR sensing system.

(EDF) using a 980/1550 wavelength-division multiplexer (WDM). An optical isolator is placed at the output of the forward-pumped EDF to ensure the unidirectional propagation of light in the cavity. A circulator and a fiber Bragg grating (FBG) are used to select the lasing wavelength. The FBG's center wavelength is 1534.26 nm with a bandwidth of 0.4 nm. Since a traditional SPR sensor is used here instead of a waveguide SPR sensor, the light in the fiber is launched into the free space from a collimator before it illuminates the sensor. Since the SPR reflectivity varies significantly only for the p-polarized beam, a polarizer is placed in the beam to make only p-polarized light pass through. After the SPR sensor, the light is coupled back into the fiber. Due to the lack of polarization-maintaining fiber components, a fiber polarization controller is put in the cavity to maximize the output. A 90/10 fiber coupler is used as the output coupler with 90% of the light coupled back to the cavity. The output power is measured by a high-resolution optical power meter (JDS Uniphase MAP+2M00).

The SPR sensor used here is based on a traditional Kretchmann configuration. The coupling prism and the substrate of the SPR sensor chip are made of ZF-7 glass with a refractive index of 1.763 at 1550-nm wavelength. The SPR chip is made of a 49-nm-thick layer of gold evaporated on the ZF-7 substrate. Index-matching fluid is used to attach the sensor chip to the prism. A microfluidic channel made of polydimethylsiloxane (PDMS) is attached on the gold layer. The sensor is mounted on a rotation stage and the optical incident angle is fixed at approximately 52.4°, which is close to the SPR angle at 1550 nm.

We perform a series of buffer-switching experiments to demonstrate our scheme's ability to enhance sensitivity. Several saline solutions centered around 1.95 wt.-% are used. For one series containing five samples from 1.925 to 1.975 wt.-%, their refractive indices are considered to be linearly dependent on the weight percent within this range and the refractive index difference between the samples with the highest and lowest weight percent is estimated to be $\sim 1.6 \times 10^{-5}$ refractive index units (RIU).

It is necessary to adjust the SPR wavelength of the SPR sensor with 1.95 wt.-% saline solution to fall near 1550 nm, but not exactly at the lasing frequency of the fiber laser, so that the change in the refractive index of the sample can cause significant changes in the reflectivity, that is, the loss through the SPR sensor. This is done by adjusting the incident angle, while an amplified spontaneous emission (ASE) fiber light source with a stable bandwidth of $\sim$ 25 nm is connected to the collimator 1 and the output from collimator 2 is measured by an optical spectrum analyzer (OSA). With this wavelength interrogation configuration, the SPR spectral response is measured. Figure 2 shows the spectral reflectivity curves when the sample is changed. The initial SPR wavelength is near 1560 nm and it increases with the increase in the concentration.

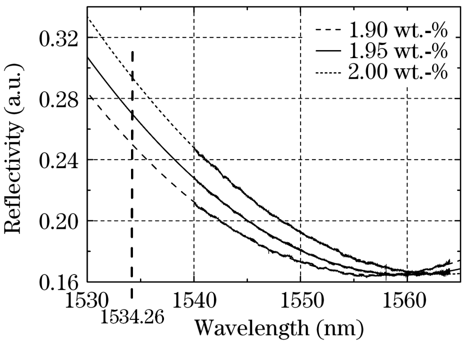

Fig. 2. Wavelength interrogation of the SPR with different samples.

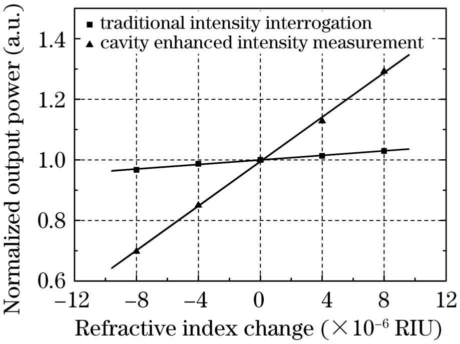

Fig. 3. Comparison of sensitivity between traditional intensity interrogation and cavity enhanced intensity measurement.

In the next step, with the 1.95 wt.-% saline solution sample in the channel, the angle of the SPR sensor is fixed and the sensor is connected into the cavity. The bias current of the 980-nm diode, that is, the pump power, is varied. It is observed that, like any other continuous-wave (CW) laser, the output power is very low until the threshold is reached, but above which it quickly increases. Our measurements show that the threshold driving current of the 980-nm pump laser is around 55 mA. Thus, the bias current is set at 55 mA and the output power of the optical cavity with five different samples (from 1.925 to 1.975 wt.-%) is measured (see Fig. 3). The output power P is normalized to that for the 1.95 wt.-% saline solution sample, defined as $P_{\mathrm{norm}} = P/P_0$, where P_0 is the output power for the 1.95 wt.-% saline solution sample. For comparison, the sensitivity under the traditional intensity interrogation scheme is also measured for the same SPR sensor under the same SPR conditions and the same set of samples. That is done by measuring the reflected power from the prism without cavity enhancement using a tunable laser whose wavelength is set to 1534.26 nm as the light source. The SPR sensing sensitivity in the optical cavity, defined as the ratio of the normalized output power change over the reflective index change $\Delta P_{\mathrm{norm}}/\Delta n$, is measured at 37.1%/($10^{-5}$ RIU), which is 9.6 times larger than the 3.9%/(10^{-5} RIU) of the traditional intensity interrogation scheme.

In conclusion, we demonstrate that by putting an SPR sensor inside a fiber laser cavity, the detection sensitivity can be significantly improved. We note that, due to the limitations in our experimental setup that is far from a fully integrated and polarization-maintained system, keeping the system stable for long-term operation is challenging. Small changes of the state of polarization, environmental temperature, and pump power can lead to changes in the operation parameters and the changes in the system sensitivity. We expect that significant improvements in the stability as well as portability and miniaturization can be made by realizing this scheme with waveguide SPR sensors[18] and the planar-waveguide-based microlaser cavity.

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