Properties of an optical multipass surface plasmon resonance technique

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A fiber optic four-pass surface plasmon resonance technique with an approach to increase the number of passes to any arbitrary number is described. Within multipass regime, reflections off the gold sample surface that reduce the reflectivity to less than 0.1\% are achieved by using a fiber optic collimator, a reflector, and a corner cube prism. In this case, the optical beam emits from and returns to the collimator. This technique holds the potential for significantly increasing the detection sensitivity of surface plasmon resonance device. © 2006 American Institute of Physics.

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Many types of electrical, mechanical, and optical sensors are being developed for biomedical research and diagnostics. Highly sensitive electrical nanowire sensors can detect a small amount of biomolecules immobilized on the surface of the silicon nanowires.\textsuperscript{1} Nanoscale cantilever showed great potential for detection of a single virus.\textsuperscript{2} Photon-tunneling sensors that integrate nanochannels with total internal reflection sensing elements have also been developed.\textsuperscript{3}

The first surface plasmon resonance (SPR) chemical sensor was developed by Matsubara \textit{et al.} in 1988,\textsuperscript{4,5} and since then SPRs have been widely utilized for chemical and biological sensing\textsuperscript{6,7} because of their cost effectiveness and ease of operations. SPR sensing elements have also been integrated with microfluidic channels for detecting biomolecules.\textsuperscript{5} Basically, SPR technique relies on the evanescent optical wave extending just above a very thin metal surface (usually gold) to sense the presence of target substance, especially biomolecules residing on the gold surface. Because the spatial extent of the evanescent wave above the gold surface is very small, just a monolayer of molecules on the gold surface can significantly affect the evanescent wave.

In SPR one detects a change in the gold surface reflectivity caused by the residing molecules.

Generally, SPR is implemented by using the Kretschmann’s configuration with a light source and a detector on opposite sides of a prism, which allows for one reflection (one pass) of the optical beam from a gold layer deposited or placed on the prism’s hypotenuse. In this letter, we introduce a fiber optic multipass SPR technique that, theoretically, can enhance the sensitivity by any arbitrary factor depending on the number of passes through the sample. That multipass SPR improves sensitivity is shown below: Assume that we sit at a bias angle $\theta_b$ below the resonant angle. The detection power is $P_1 = a R(i)$ for one pass, and is $P_n = b R^n(i)$ for $n$ pass. For a fair comparison, assume the bias power for the $n$ pass matches that of one pass; i.e., $a R(i_b) = b R(n i_b) = P_0$. Taking derivatives with respect to $\theta$, one have for the one and $n$ passes

$$\frac{dP_1}{d\theta} = P_0 \left[ \frac{1}{R(i_b)} \frac{dR}{d\theta} \right],$$

$$\frac{dP_n}{d\theta} = n P_0 \left[ \frac{1}{R(i_b)} \frac{dR}{d\theta} \right] = n \frac{dP_1}{d\theta}.$$  

Thus at any bias level, $dP_n/d\theta$ is intrinsically greater than $dP_1/d\theta$ by a factor $n$, the number of passes.

The discussion described above provides the motivation for designing a multipass SPR device. The embodiment of the multipass SPR device is shown in Fig. 1. Several components are mounted on the prism holder as shown. They are the right-angle prism, the fiber optic collimator/reflective unit, and a corner cube prism. The fiber optic collimator and reflector are fixed in one unit and they rotate in unison. The gold-plated substrate target is placed on the prism surface. The collimator delivers an optical beam to the substrate. The optical beam propagates toward the corner cube following a reflection from the substrate’s gold surface. The backward reflected beam off the corner cube is exactly parallel (within 2 arc sec) to the incident beam. This beam hits the gold surface the second time and proceeds towards the reflector. The normal of the reflector is engineered parallel to the beam emanating from the fiber collimator, ensuring that the back-

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Surface plasmon resonance device with a fiber coupler implemented to inject and detect light.}
\end{figure}

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ward reflected light from the reflector retraces the previous light path, eventually returning the beam back into the collimator after impinging the gold surface four times. The provision that the return light signal propagates back into the collimator fiber waveguide allows for easy detection and signal processing using standard fiber optic techniques. The whole unit is compact and portable.

Pulse operation of the laser light is needed to increase the number of passes beyond 4. The fiber optic configuration external and independent of the aforementioned SPR device is used and is shown in Fig. 2. This application uses a light wavelength of 1.53 μm for convenience because erbium-doped fiber amplifier (EDFA) for signal amplification is readily available commercially. The initial input optical pulse driven by a pulse generator enters the EDFA. The pulse travels down the optical circulator and into an optical splitter, then into the SPR device. Then return pulse from the SPR, which has already taken four passes through the gold surface, is routed into the same EDFA through a fiber splitter. After the pulse reemerges from the SPR device it has taken another set of four passes through the gold surface; hence the total number of passes has increased to 8. The process continues indefinitely; thus, theoretically, the number of passes can extend to infinity. A fiber delay line temporally separates the individual pulses. The polarization controllers are adjusted so that all pulses entering the SPR are TEM polarized. The recirculating pulse sequence is shown in Fig. 3 for the case of 0.3° below resonance (solid line) and 0.12° below resonance (dashed line). The reduction in amplitude of subsequent pulses is due to the extra optical loss experienced by the pulse after traversing a round-trip through the optical system.

Experimentally, the collimator-reflector is angle scanned through the SPR resonance. A log plot of the reflectivity versus the angle is shown by symbols in Fig. 4 for the case of one, four and eight passes through the gold surface. For the one-pass measurement, the corner cube was removed and replaced with a detector. It is noted that the measured minimum reflectivities are about (0.5 and 0.13)×10^{-2} for the case of one and four passes. For eight passes, the power level at minimum reflectivity is below the detectable limit (0.04 mV). In order to fit the experimental results to a calculated profile, it is necessary to consider the collimator’s beam divergent angle since the reflectivity dip is very sharp. The divergent angle φ for the collimator used is 0.2° full width at half maximum. The measured resonance profile R(θ) is given by

\[ R(\theta) = \int H(\theta - \theta') R_{\text{cal}}(\theta') d\theta', \]

where \( R_{\text{cal}}(\theta) \) is the calculated resonance response and \( H(\theta) \) is the transfer function describing the effect of the divergent beam. We assume that \( H(\theta) \) is given by a Gaussian function with \( H(\theta) = \sqrt{2\pi\sigma}^{-1} \exp(-\theta^2/2\sigma^2) \). The width parameter \( \sigma \) is given by \( \sigma = (\varphi/2)[1/(1.5)1/(\sqrt{2}\ln(2))] \) for one pass and \( \sigma = (\varphi/2)[1/(1.5)1/(\sqrt{2}\ln(2))] \) for multiple passes in which the beam returns back to the collimator. The factor 1.5 accounts for the reduction in beam divergence upon entering the prism due to Snell’s law, and the factor 0.1 accounts for the reduction of beam divergent effect on \( R(\theta) \) due to the increased beam diameter when the beam returns to the collimator after encountering four passes through the sample. In fact, \( \alpha \) is equal to the coupling efficiency back into the collimator, which is measured to be 10%. For one pass \( \alpha = 1 \), and for multiple passes \( \alpha = 0.1 \). The following parameters are used in the calculation. Gold layer thickness was 45 nm. Refractive indices of BK-7 and Au at 1530 nm wavelength were 1.500 65 and 0.4+9.7i, respectively. \( \varphi = 0.2° \), and \( \alpha = 0.1 \) or 1 for multiple passes or one pass, respectively. The four-pass and eight-pass results were described by \( R^4(\theta) \) and \( R^8(\theta) \), respectively. Calculated \( R_{\text{cal}}(\theta) \) was for air interface which was the case in this experiment.

Lines are calculated results using parameters described above. Calculated and measured values agree reasonably well. The minimum reflectivity for the four-pass case is 1.3 \times 10^{-5}. The minimum reflectivity (1.7 \times 10^{-6}) for the eight-
pass case is not displayed because its value is below our detectable limit. It is noted that the collimator’s beam divergent angle $\varphi$ of 0.2° does have a significant effect on the reflectivity. For instance, if $\varphi$ = 0 instead of 0.2° then $R$ is 0.12 instead of 0.47 for the one-pass case.

It is known that the extent of the evanescent wave is longer for a longer wavelength. However, the choice of 1530 nm is not generic to this technique. A shorter wavelength (670 nm) could also be used, only the costs of fiber components is significantly higher. In any case, the intrinsic sensitivity at 1530 and 670 nm wavelengths may actually be similar because the resonance is much sharper at 1530 nm wavelength, although the angle shift is much larger at 670 nm: If the gold surface is perturbed by a 1 nm thick material with a refractive index of 1.45, calculations indicate that at 670 nm the resonant angle shift is 0.093°/nm, and is 0.013°/nm at 1530 nm. However, the resonant half-widths at 670 and 1530 nm are 0.35° and 0.04°, respectively. Thus, if one sits at a bias angle and measure the reflectivity change, the intrinsic sensitivity is roughly the same for both wavelengths. The number of passes, will determine the improvement. If the choice of wavelength is 1530 nm, which is the wavelength used for this demonstration, the appropriate sensing measurement would be to sit at a fixed bias angle and measure the reflectivity change. Note that a 30 nm gold thickness can yield a smaller reflectivity, but the resonance is also wided.

A scheme for implementing a four-pass surface plasmon resonance sensor using fiber optic technology is described. The smallest reflectivity is 0.1% for the four-pass case. Biasing the device at the low reflectivity with multiple passes offers the potential for the largest percentage change in power. This SPR device is compact, portable, and should have high detection sensitivity. A fiber optic scheme to increase the number of pass to any arbitrary number is also given.
