

Initial demonstration of a local, evanescent, array coupled biosensor concept

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Abstract—A concept for a novel, compact, immunoassay biosensor that can simultaneously sense multiple analytes simultaneously is being investigated. The dielectric planar waveguide sensor relies on modulation of the local evanescent field coupled into an array detector. Proof of concept experiments carried out using near-field scanning optical microscopy (NSOM) on a 17 nm thick pseudo-adlayer demonstrated high sensitivity with an optical SNR of approximately 55:1. The measured results agree with numerical simulations.

I. INTRODUCTION

Conventional optical waveguide sensor techniques such as attenuated total reflection [1], Raman scattering [2], and fluorescence spectrometry [3], have been well investigated and employed in biosensor applications. Although these techniques enjoy low optical loss and high sensitivity, their applications are restricted by the limited number of analytes that can be simultaneously detected using a single waveguide and large inaccuracy when sensing ultra-small quantities.

Therefore, there is presently a need for novel optical waveguide sensors with capabilities to detect small volumes of multiple analytes while possessing comparable sensitivity to the conventional techniques for various medical, biological and environmental situations. In order to meet this requirement, we are developing a local, evanescent, array coupled (LEAC) biosensor based on a planar, dielectric waveguide [4]. The mechanism of the LEAC sensor relies on specific binding of an analyte target to one of several localized regions of immobilized biological molecule probes to modify the waveguide cross-section and thus the local evanescent field. A buried array of detector elements along the length of the waveguide, each opposite a region of specific antibody type, can sense the modification in the evanescent field due to local adlayers of bound analytes as seen in Fig. 1. Sensing of targets such as

proteins, DNA, viruses, and bacteria are possible with this device.

In proof-of-concept experiments, the evanescent field has been monitored via an alternative method of near-field scanning optical microscopy (NSOM). Similar to the underlying detector array, NSOM is used to directly measure the evanescent field and thus the optical intensity on the upper surface of the waveguide. The NSOM technique has been employed to study basic optical phenomena in waveguides such as propagation loss, spatial mode profiles, and modal interference [5-10]. In this work, NSOM is used for the first time to analyze a waveguide's evanescent field change due to an adlayer. The measured results are shown to be in agreement with numerical simulations.

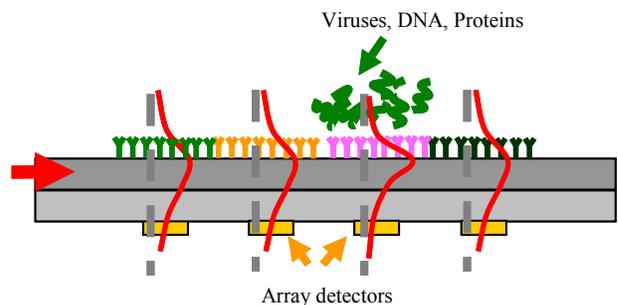


Fig. 1. Bio-adlayers binding on a single-mode optical waveguide effectively increases the thickness of the core layer, thus decreasing the evanescent field tail absorbed by the underlying detector. The solid curves illustrate the waveguide mode profiles at different positions along the light propagation direction.

II. FABRICATION AND NSOM APPARATUS

The $\text{SiN}_x/\text{SiO}_2$ waveguide studied was fabricated using traditional sputtering, optical lithography, and etching methods. A 105 nm thick SiN_x film was deposited on a SiO_2/Si wafer using NH_3/argon sputtering, where the SiO_2 lower cladding thickness is about 2 μm . A 2 μm wide ridge waveguide core was defined by partially dry etching the surrounding SiN_x layer in CF_4/O_2 plasma. In the latter processing step, the etch depth and thus ridge height is determined to be 21 nm. An artificial adlayer was created by masking 10 μm wide bars oriented perpendicular to the waveguide, and etching the exposed SiN_x an additional 17 nm. The waveguide core thickness after the adlayer etch is 88 nm, and the ridge depth is 21 nm. The top surface of the SiN_x film is left exposed to the air that serves as the upper cladding, allowing the NSOM to examine the evanescent field there. Refractive indices of the core (SiN_x) and lower cladding (SiO_2) are $n=1.8$ and 1.45, respectively. Edge facets of the samples were polished for end-fire coupling of a 654 nm laser diode via visible single mode fiber (4/125 μm core/cladding diameter).

To analyze the interference phenomenon in a proof-of-concept configuration without the underlying detector array, NSOM is used to directly measure the evanescent field on the upper surface of the waveguide. The NSOM instrument

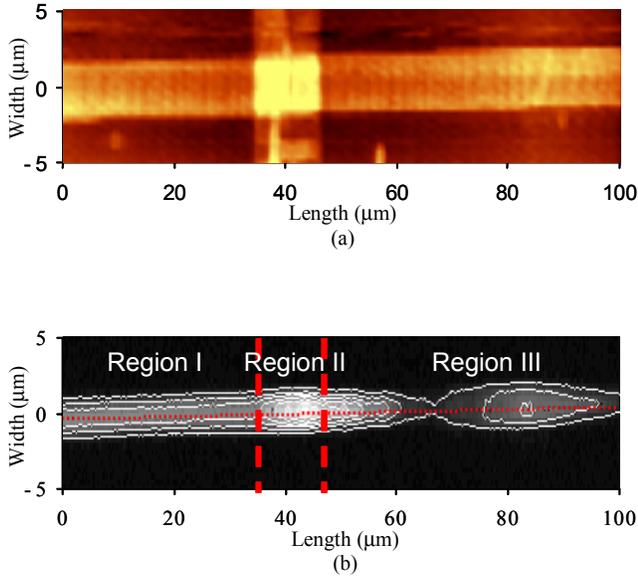


Fig. 2. (a) Grayscale plot of the topography along the waveguide and (b) grayscale and contour plot of measured light intensity for the same region. The horizontal dotted line shows the centerline used for the longitudinal intensity plot in Figure 3. The three regions of the waveguide before, coincident with, and after the adlayer are referred to as Regions I, II, and III, respectively. Note the horizontal and vertical scales are different.

used is an α -SNOM system from WiTec that is able to simultaneously measure light intensity and surface height. The system has a lateral-scanning resolution of approximately 10 nm. It relies on a micro-fabricated hollow aluminum pyramidal tip to convert an evanescent wave to a propagating wave by locally frustrated total internal reflection [11]. A sub-wavelength size pinhole centered in the tip is initially aligned to maximize the signal received by a photo multiplication tube. Similar tips can also be found in generic atomic force microscopy (AFM) systems, but without apertures. A reference laser beam is reflected from the tip cantilever to a segmented photo detector to determine the topography of the waveguide sample.

II. MEASUREMENTS AND SIMULATIONS

NSOM experiments yielded light intensity and topography maps simultaneously. Figure 2(a) shows a topography image over a 10 $\mu\text{m} \times 100 \mu\text{m}$ scanned area based on surface height information. The waveguide width appears slightly larger than 2 μm because of the finite NSOM tip size. Light is coupled into the waveguide approximately 4mm to the left of the area shown. The three regions of the waveguide before, coincident with, and after the adlayer are referred to as Regions I, II, and III, respectively. Figure 2(b) represents the corresponding contour plot of the measured light intensity from the same scanned area. The image clearly shows a strong change in the optical evanescent field when the wave encounters the adlayer region. Modal calculations determined that the waveguide supports only one guided mode, TE_{00} , in all three regions. The 4mm distance from the input facet assures a

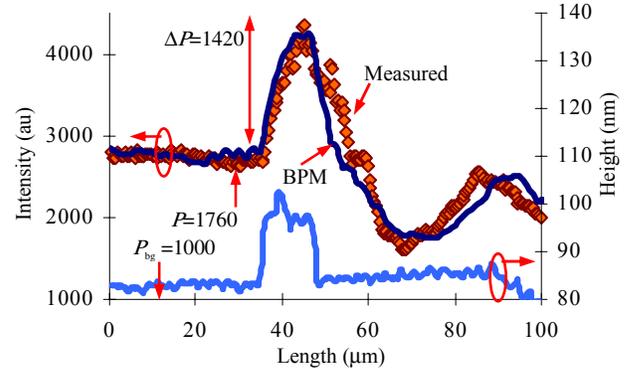


Fig. 3. Longitudinal dependence of the optical field (top) based on BPM simulation (solid) and NSOM measured data (diamonds) and surface height (bottom). The input power level, after subtracting the background ($P_{bg}=1000$ counts) is $P=1760$ counts and the maximum intensity change due to the existence of the adlayer is approximately 1420 counts.

stable mode in Region I. As a result, a Gaussian shaped optical field profile is found corresponding to the guided

TE₀₀ mode in Region I in agreement with the modal calculation.

Optical propagation through the waveguide with the adlayer structure was also simulated by two-dimensional bidirectional beam propagation method (BPM) [12] using commercial software by RSoft. The incident beam was assumed to be the TE₀₀ mode at a wavelength of the 654 nm. The intensity distribution from the BPM simulations is also presented in Figure 3, along with the corresponding surface height. The BPM simulation results, which include no adjustable parameters, agree very well with the measured results. The input power level, after subtracting the background ($P_{bg}=1000$ counts), is $P=1760$ counts and the maximum intensity change, in Figure 3, is $\Delta P=1420$ counts. Thus optical intensity modulation capability of the adlayer is about $\Delta P/P=81\%$. Noise in the measured intensity originates from the scattered light due to the surface roughness. The average noise level is approximately $P_n=26$ counts and therefore the estimated optical SNR is 55:1. This important result supports the potential application of this waveguide sensor configuration to analyze nanoscale adlayers, such as molecular monolayers.

In Region III, a large, damped oscillation of the evanescent field is observed, and this oscillation is also predicted by BPM calculations. The effective index of the guided mode is 1.459 and its attenuation coefficient is estimated to be 8dB/cm [10] based on attenuation measurements well away from the adlayer. In addition to the guided mode, a strong leaky mode of effective index 1.441 is also excited by the field perturbation in the adlayer region, which gradually dissipates in Region III by leaking into the lower cladding (SiO₂, $n=1.45$). Thus a transient modal interference is found in the Region III with a period approximately 36 μm corresponding to the difference in the effective indices.

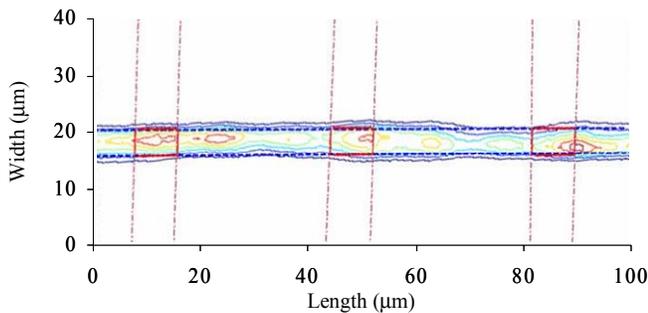


Fig. 4. Contour plot of measured light intensity along the waveguide. Light propagates from left to right. The vertical dashed lines show the locations of the adlayers and the horizontal dashed lines indicate the edges of the waveguide.

Another measurement was done on 8nm-thick, 5 μm -long adlayers spaced by 35 μm apart. The region outside the 3 μm wide ridge waveguide was etched to a depth of 31 nm. The optical field, shown in Figure 4, appears noisy

due to multimode interference. Despite this noise, the signal to noise ratio is approximately 40:1. Detection of yet thinner adlayers should be readily possible in single mode waveguides.

III. SUMMARY

We are developing a local, evanescent, array coupled (LEAC) biosensor, which provides high optical sensitivity to multiple small localized adlayers. NSOM was used for the first time to directly measure the change in the optical intensity due to the adlayers on the waveguide. In this initial demonstration, pseudo adlayers of the same material as the core are studied. For a 17 nm adlayer, the change in the optical intensity can be as high as 81%, with a SNR of approximately 55:1. Observed optical intensities were in good agreement with BPM simulations. A transient optical intensity oscillation is found subsequent to the adlayer and resulted from the modal interference of the guided mode and a transient leaky mode. The strength of the oscillation may be a useful indication of the adlayer's optical properties.

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