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Phase sensitive array detection with polarisation modulated differential sensing

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Abstract

It has recently been shown that polarisation modulated differential surface plasmon sensing can be used to monitor refractive index changes of approximately 2×10^{-7} refractive index units. The information for these measurements is carried by a small-modulated light component and a relatively large constant background signal. These measurements have, hitherto, only been carried out as point measurements. In this paper we demonstrate that multipoint measurements can be obtained using a CMOS camera array that directly detects the amplitude and phase of the oscillating component of the light. The effectiveness of the parallel measurement is demonstrated by monitoring the changes in a waveguide mode as the refractive index of the dielectric layer is changed by exposure to ultraviolet radiation. This paper demonstrates the potential of phase sensitive CMOS detection in applications where spatially resolved differential imaging is required, especially in the field of chemical and biological sensing.

Keywords: Optical sensor; Array detection; Biosensor

Surface plasmons (SPs) [1] have been used in chemical and biological sensors for a number of years [2], as they are very sensitive to changes at an interface. They respond to refractive index changes of a bounding dielectric (or equivalent thickness of an overlayer) at the surface of the SP active medium, caused by some chemical or biological process or by the appearance of chemical or biological matter. Some of the more sensitive SP sensing methods utilise differential optical techniques [3–5], which usually involve monitoring the reflectivity variation as a function of angle or wavelength. Some authors have recently reported that monitoring the phase of the signal reflected from the sample provides a more sensitive measurement compared to monitoring intensity. The obvious way to introduce a phase measurement into SP sensing is to introduce an interferometer into a conventional Kretschmann based SP sensor [6]. Perhaps the easiest way to do this is to illuminate with mixed (TM and TE) polarisation states and analyse the polarisation of the returning light since the two incident polarisation states form two arms of an interferometer reflecting with different phase shifts. One version of this system involves monitoring the azimuth of the differential of the reflected polarisation ellipse [7,8]. The key feature of this method is that the polarization state is dynamically dithered so the change in polarisation is encoded as a time varying signal synchronous with the polarisation dither.

Consider a system which allows an electromagnetic resonance to be optically excited by one of the two linear orthogonal polarisations (TM – transverse magnetic or TE – transverse electric) at the appropriate wavelength, angle and polarisation. Through the resonance condition the phase of the reflected signal also changes rapidly. If linearly polarised light is incident upon the system under the appropriate conditions for the resonance to be excited, and at some arbitrary polarisation angle such that it consists of both TM and TE polarised components, then the polarisation component which excites the resonant mode will undergo a considerably greater intensity and phase change compared to the other, non-exciting, polarisation component. The resultant light therefore consists of orthogonal polarisation components, which are phase shifted with respect to each other, or in other words the reflected light becomes elliptically polarised.

The azimuth and ellipticity of this elliptically polarised light are very sensitive to changes in the intensity and, more so, the phase of the reflected light component which has excited the

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mode, and as such are obviously very sensitive to the excitation angle/wavelength of the resonance. Therefore, monitoring a change in the azimuth and ellipticity of the reflected light gives a very sensitive measure of any change in the resonance. This idea is the basis of a sensor based on polarisation monitoring.

Indeed, it is not necessary to monitor both the ellipticity and azimuth of the light in order to detect a change in the resonance, only the azimuth need be monitored as this is usually more sensitive to changes in the resonance, and is also easier to measure accurately. Indeed, the key to basing a useful sensor on this technique is develop a sensitive method for monitoring the azimuth of the reflected light.

Optical differential measurements usually use a small modulation of either the incident wavelength or angle, and phase sensitive detection at the modulation frequency allows the differential signal to be obtained. This differential signal is more sensitive to resonance changes compared to the corresponding non-differential method. An additional advantage of such differential methods is that, since a resonance peak/trough will give a zero in the differential signal, feedback loops can be used to lock to the zero (by changing the central angle/wavelength of the dither). This provides ease of measurement (since it is now the feedback signal which is monitored removing the need to measure the resonance position), and removes any effect of varying light levels.

Clearly something similar would be useful for a polarisation monitoring sensor. One non-differential method of monitoring the azimuth of the elliptically polarised light would be to place a polariser in the reflected light and change the angle of the polariser until a maximum in the intensity is found. The angle of this polariser corresponds to the azimuth of the polarisation ellipse. If the plane of polarisation were modulated by a small amount, and a PSD monitored the signal at the modulation frequency, the differential of the light intensity as a function of this polariser angle would be obtained in a similar way to the other differential methods described above. This dithering can be achieved in a number of ways, with recently published work utilising Faraday rotators [7] and liquid crystal cells [8]. These two methods have the additional advantage that they enable simple electrical feedback systems to be employed. This then allows for polarisation modulated differential sensing, with a full description of the technique being discussed elsewhere [7,8].

One limiting factor in the employment of these differential techniques is that, as discussed previously, a PSD is used to obtain the differential signal. Therefore, they are implemented as 'single pixel' techniques unless multiple PSDs are utilised, which is not a practical option for more than a few pixels. Analogue circuitry in CMOS is a promising route to producing many phase sensitive detectors on-chip, these allow the amplitude and phase of the modulated signal to be obtained on each pixel. The chip used in this study has been described in more detail elsewhere [9,10]. In essence, the detector consists of an array of 64×64 pixels, with 64 lines of processing electronics so that all the pixels in a single line may be processed in parallel. The array is scanned electronically so that one line of detectors can be addressed at any particular time; thus allowing us to produce the images presented in this paper. The output from the on-chip photodiode is passed through a hysteretic differentiator circuit which amplifies the modulated signal and acts as buffer for the background, thus greatly increasing the proportion of modulated light. The signal is then sampled (and averaged) at the modulation frequency. The circuit has two channels which may be clocked independently so that different phases of the incoming waveform may be sampled in each channel. This allows for flexible operation of the detector chip. To operate in phase sensitive lock-in mode the two channels are clocked in quadrature, so that the real and imaginary parts of the modulated optical signal may be acquired. In addition to detecting the modulated light the chip also detects the background dc light to give the type of image found with a conventional CCD camera. Detectors capable of monitoring small-modulated signals over a large array could open the door to a new generation of sensors which will allow many different areas of a sample to be examined simultaneously with the differential technique, involving, for instance, either wavelength dither or, as reported in this paper, polarisation dither. In addition, direct imaging of differential signals in real time can be obtained. In this work these new detectors are used with a differential polarisation modulation technique to prove, in principle, that this is possible.

As indicated previously, SP excitation is often used in sensing applications as SPs are very sensitive to refractive index changes at a surface [1]. However, it is also possible to perform equivalent experiments utilising the excitation of a waveguide mode. With SP excitation any RI change of the bounding dielectric causes a shift in the angular position of the SP resonance, which is monitored to measure the RI changes. Equivalently, with waveguide mode excitation a change in the RI of the waveguiding medium itself causes the angular shift of the waveguide resonance, which is the measure of the RI change. In the experiment described here a UV sensitive photoresist layer is used as the waveguiding medium. Upon illumination with UV the refractive index of the photoresist layer increases, causing the excitation angle of the waveguide mode to increase. This change is monitored using the differential polarisation modulation technique together with the phase sensitive CMOS detector. This allows a spatially resolved differential image of the exposure area to be monitored as a function of time, demonstrating the potential of these new detectors with differential methods.

A 30 nm thick silver film is thermally evaporated onto a silica substrate, which is then coated with approximately 320 nm of photoresist (Shipley SPR700-1.2). The silica substrate is index-matched to a silica prism to allow excitation of the first order TM waveguide mode at an incident angle just beyond the critical edge. The choice of this TM waveguide mode is arbitrary as a TE waveguide mode would work equally well. By setting up this system such that the angle of incidence is initially slightly greater than the waveguide excitation angle, the irradiation of UV light causes the waveguide mode to pass through the angle of incidence chosen.

The light from a 632.8 nm He–Ne laser is linearly polarized at 30° (where 0° is defined as giving pure TM-polarized light). Following this the light passes through a polarisation modulator which dithers the plane of polarisation before the beam is expanded and collimated. This beam is then incident upon the prism-coupled waveguide system, with the reflected light passing through a second polarizer, also oriented at 30°, before being imaged onto the detector array. The polarisation modulator used in this experiment is a 5 μm thick ferroelectric liquid crystal (LC) [11] cell (SCE8* from Merck) with a 1 kHz sinusoidal voltage (∼1 V) applied to it, which in turn produces a 1 kHz sinusoidal modulation of the plane of polarisation. A schematic of the apparatus is shown in Fig. 1.

The CMOS detector provides amplitude and phase information of the modulation of the reflected light provided by the polarisation modulator. This is different to the information obtained by a PSD, which gives a vector amplitude at a set phase (equivalent to the differential signal). However, the information from the CMOS array can be easily converted to an equivalent signal as would be obtained from a PSD. The maxima and minima of the polarisation ellipse then occur as zeros in the differential signal, and the angular position of these extrema change as a function of the refractive index of the waveguiding medium. In the previous studies using the differential polarisation modulation technique feedback was utilised to maintain a zero in the signal. In this study this has not been employed due to the difficulty in implementing it in the present generation of detector arrays, with the differential signal being directly monitored instead. The CMOS detector also allows the background light to be measured, producing a direct reflected intensity image.

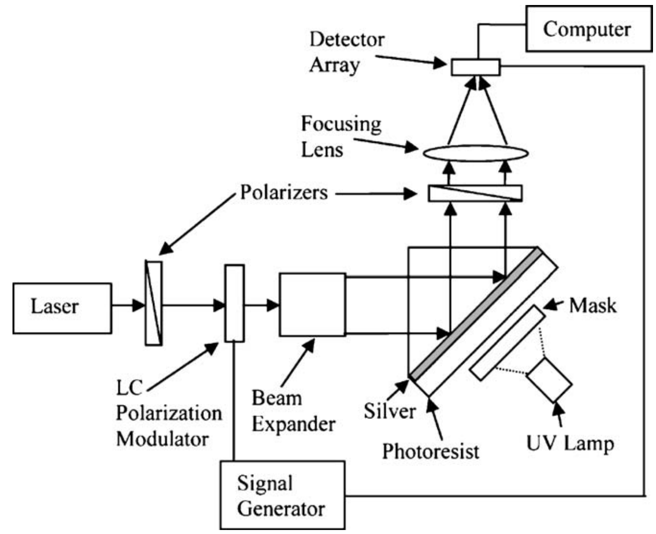

Fig. 1. Schematic diagram of the experiment.

A mask containing a spot aperture was placed over the photoresist layer before UV illumination with light from an 8 W UV lamp emitting 365 nm radiation. After an exposure of 80 s the photoresist in this spot region was totally exposed (giving a refractive index change of the order of 1×10^{-2} RIU), and

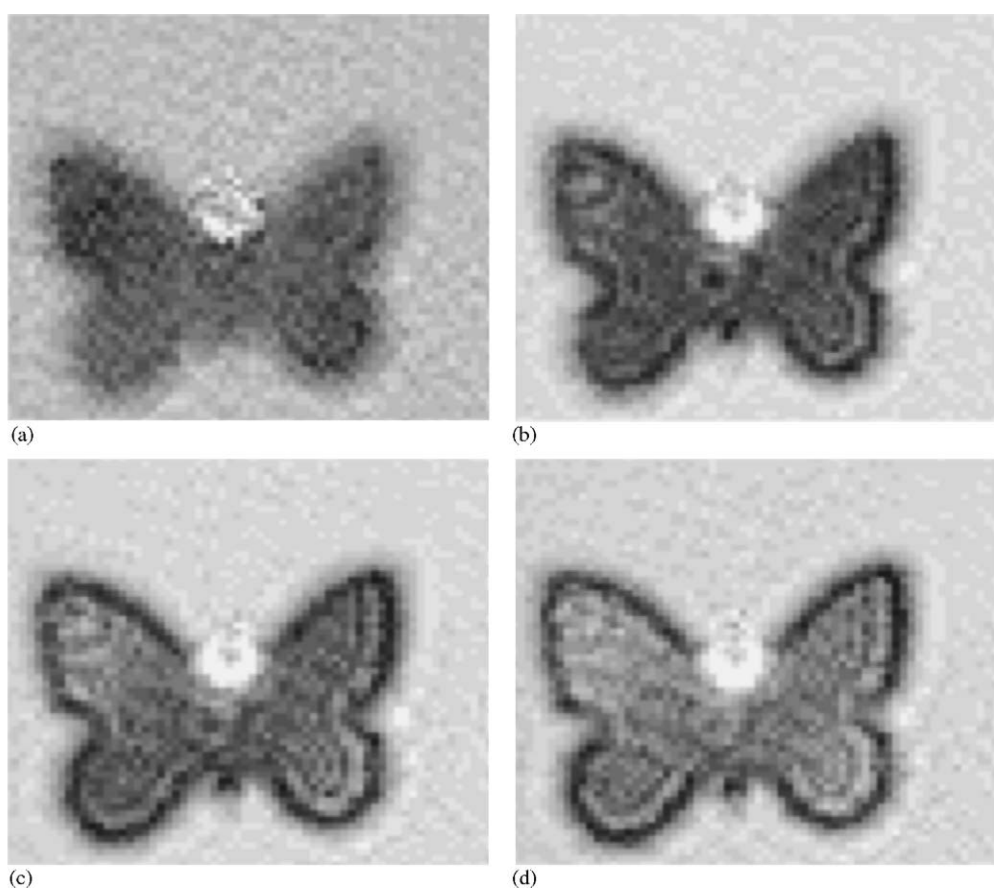

Fig. 2. Non-differential reflectance images. The central white circle corresponds to the initially exposed aperture area. (a) 10 s exposure, (b) 30 s exposure, (c) 50 s exposure, and (d) 70 s exposure. Grey scale range for (a) is −0.04 (black) to 0.01 (white), and for (b), (c), and (d) is −0.1 (black) to 0.01 (white).

the small dot of exposed photoresist was used to set the incident angle required for the experiment, and also to align the reflected beam on the detector array. The pictures obtained from the detector array immediately after this are described as 0 s of illumination.

Following this, the spot aperture mask was removed and replaced by a second mask containing a larger butterfly shaped aperture. The system was then illuminated with UV again, with pictures being obtained at 10 s intervals, up to 80 s. The images obtained underwent post processing by subtracting the zero seconds (pre-exposure) data, and by dividing the data by a gain factor for each pixel row obtained by uniformly irradiating the detector and taking an average value for each row. The results for the differential (of the polarisation ellipse) and non-differential (direct reflectivity) measurements are shown in Figs. 2 and 3.

By orienting the input and output polarisers parallel to each other it is clear that when the incident angle is well above or below the waveguide mode the differential signal will be zero (the phase change/intensity of the two orthogonal polarisation components is almost the same producing almost unchanged linearly polarised reflected light. Since the polarisers are parallel to each other this will correspond to a maximum in the polarisation ellipse and hence a zero in the differential signal.) Also, when the excitation angle of the waveguide mode has been increased close to the angle of incidence the resultant change in the azimuth of the reflected light is approximately 90°, and therefore the output polariser is sampling the minimum of the polarisation ellipse and a zero will again be expected. Therefore, as the waveguide mode passes through the angle of incidence due to the UV induced RI change, three zeros will be expected: after zero UV illumination, after sufficient UV illumination to position the waveguide mode at the angle of incidence, and when the UV illumination is sufficient to have moved the waveguide mode right through the angle of incidence. In the regions between these zeros (when the incident angle is on the slopes of the waveguide mode) the signal will be positive or negative depending upon which side of the resonance the angle of incidence is, and the phase at which the CMOS detector is monitoring. To summarise, as the waveguide mode passes through the angle of incidence the differential of the polarisation ellipse signal would be expected to change as: zero, positive (negative), zero, negative (positive), zero.

Now, let us first consider Figs. 2a and 3a (10 s of UV exposure). In Fig. 2a (the non-differential intensity signal) it is clear that the waveguide mode is starting to pass through the angle of incidence due to the change in RI of the photoresist guiding medium. Comparing this to the corresponding differential plot in Fig. 3a the signal in the exposed area has become positive. After a further 20 s of UV exposure (Figs. 2b and 3b) the non-differential plot shows a lower intensity in the exposed region, with the corresponding differential plot showing a wide variation in value throughout the same region. Indeed, this is the time at which the waveguide mode has shifted position sufficiently

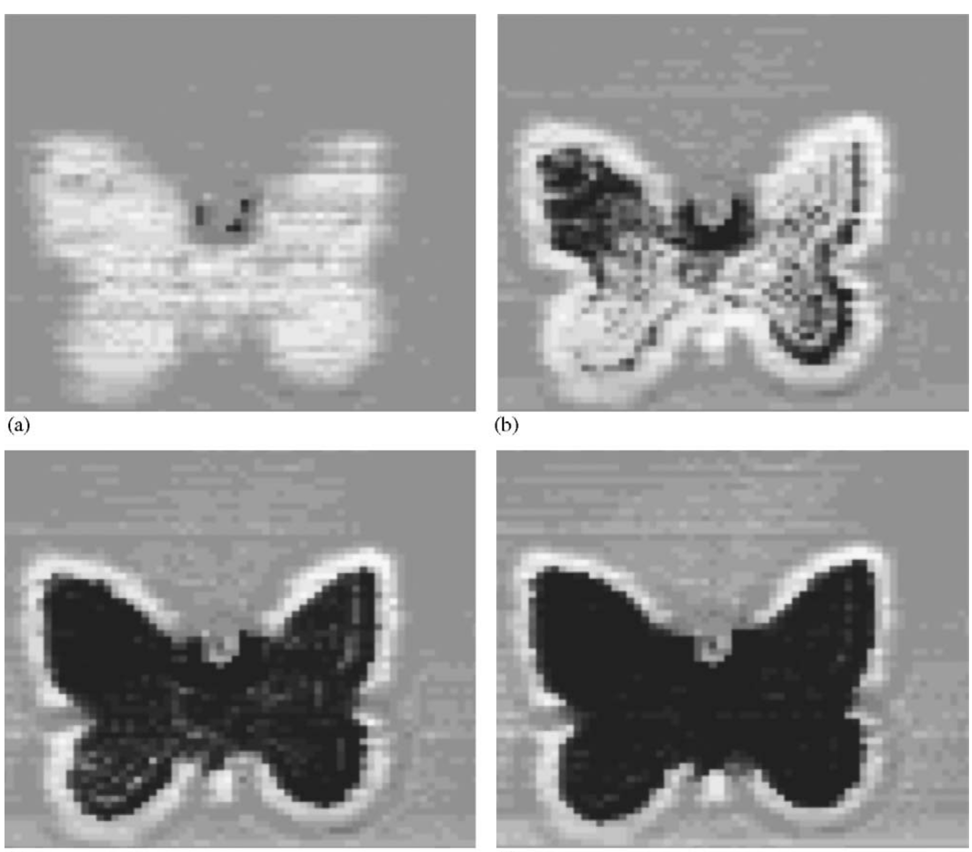

Fig. 3. Differential of polarisation ellipse images. The central grey circle corresponds to the initially exposed aperture area. (a) 10 s exposure, (b) 30 s exposure, (c) 50 s exposure, (d) 70 s exposure. Grey scale range for all are −0.4 (black) to 0.3 (white), with zero being the mid grey around the outside of the butterfly shape.

that the differential signal in the exposed area would be expected to be zero once more. However, due to inhomogeneities in the photoresist and exposure energy, in some areas the waveguide mode has shifted position slightly more, or less, than in other regions. Due to the sensitivity of the technique there is a wide variation in the differential signal in these areas.

After a further 20 s exposure the waveguide has shifted beyond the angle of incidence, as evidenced by the lightening of the exposed region in Fig. 2c, and the mostly uniform negative value of the differential signal in Fig. 3c. One point to note is the different values around the edges of the mask shape (a darker region in Fig. 2c). This is due to slightly different exposure energies around the edge of the mask, meaning that this region lags the central exposed area. This is also evidenced in the differential plots where the signal near the edge of the mask shape changes rapidly from white (positive) to black (negative), indicating that at some point near the edge the waveguide mode is at such a position as to produce a zero in the differential signal, as would be expected for a region which had experienced less exposure. Figs. 2d and 3d show the waveguide mode having passed further through the angle of incidence. For subsequently longer exposure time there was very little variation in the plots obtained, except around the less exposed edges. The fact that the differential plot remains highly negative for these longer exposure times shows that the RI change upon total exposure of the photoresist is not sufficient to move the waveguide mode totally through the angle of incidence.

In this paper a differential ellipsometry technique has been utilised with a waveguide mode and one of a new generation of phase sensitive CMOS array detectors to demonstrate arrayed, spatially resolved, differential measurements. A UV-induced refractive index change of a photoresist waveguiding medium has been visualised with this system. This experiment has demonstrated that these phase sensitive CMOS detectors could have a large impact where any differential imaging is required, particularly in the field of chemical and biological sensing. There is no doubt that the experiments described here are representative of a very important class of sensor applications where there is a need to acquire spatially resolved information over the area of the sensor.

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Biographies

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