

Description

This invention relates to optical sensors and, in particular, to sensors based on the use of surface plasmon-polaritons (SPP) and guided modes for coupling orthogonal radiation modes.

SPP based optical sensors work on the principal of detecting changes in the SPP resonance as a thin layer on the metal which supports the SPP is changed in either dielectric constant or thickness.

In general there are two ways of monitoring SPP resonances

(a) change in reflectivity as a function of angle of incidence (momentum of the photons)

(b) change in reflectivity as a function of wavelength (energy of the photons).

Typical devices use a grating coated in an opaque layer of gold or silver and the system is set so that the detector examines the edge of the resonance - the region of steepest gradient in R v. θ or R v. λ . Any shift in the SPP resonance is then recorded as a change in received intensity.

We have found that it is advantageous to construct devices based on a procedure which involves not the detection of an SPP resonance minimum but a maximum.

This is achieved by rotating the grating through 45° with respect to the plane of incidence and using crossed input and output polarisers.

An input beam having TM polarisation will then give zero output for a detector set for TE except when the angle of incidence (momentum) or wavelength (energy) corresponds to the excitation of an SPP on the grating surface. Because the grating grooves are at 45° to the plane of incidence strong TM to TE conversion occurs and for the optimum depth grating over 50% conversion is readily achieved. Thus devices may be based on the principle of detecting a large signal on a weak background and monitoring this change in signal.

If we modulate the source then we can detect at the modulation frequency increasing the signal to noise.

The extra momentum required to couple photons directly to a surface plasmon-polariton at a metal/air boundary may be provided by the SPP-carrying surface being a grating because a grating, if rotated out of the plane of incidence, is also capable of converting p (TM) radiation into s (TE) radiation then the SPP may be coupled to, with suitable choice of grating orientation by any polarisation. The strength of coupling to the SPP has been studied as a function of ϕ , the angle between the normal to the plane of incidence and the grating grooves, using a photoacoustic technique. Because of symmetry constraints, at $\phi = 0$ only p-polarised light couples to the SPP while at $\phi = \pi/2$ only s-polarised light is coupled.

In the present example the p to s conversion, through generation of the SPP is examined as ϕ is changed from 0 to $\pi/2$. For these two limits no p-s conversion occurs while at $\phi = 45^\circ$ conversion as high as 66% is possible. This p-s conversion has previously been recorded in planar systems with tilted uniaxial or biaxial layers and utilised to fully characterise the optic tensor through the study of guided modes. Symmetry breaking is provided by the grating grooves as opposed to the out of plane optical axis. With conventional optical studies of SPP resonances a minimum in reflectivity is recorded at the plasmon angle, but we record a maximum.

In German Patent 3802538 there is described an arrangement in which a magneto-optical disc stores information read by polarised light with the polarising axis changed by the Kerr effect. The optical head uses a laser beam which passes through a lens, beam splitter and focussing lens. Reflected signals are directed through a half-wave plate and pass to a polarising beam splitter incorporating a dielectric film. The component signals are detected by a two-part photodiode which feeds a differential amplifier.

According to the present invention there is provided optical sensing apparatus characterised in that it incorporates surface plasmon-polariton means for converting radiation between s and p modes together with means for detecting a maximum in conversion between said modes.

The invention will now be particularly described with reference to the accompanying drawings, in which:

Figure 1 shows is a schematic diagram of apparatus used to obtain measurements on SPPs;
Figure 2 shows a prototype for detection of the angle of the SPP maximum using a divergent source and a split detector.

Figure 3 shows a prototype for detection of the wavelength of the SPP maximum using a polychromatic source and a split wavelength detector;

Figure 4 shows p to s coupling, R_{ps} as a function of angle of incidence at different ϕ for a grating with groove depth of 55.4nm;

Figure 5 shows R_{ps} peak height as a function of angle ϕ for a grating with groove depth of 55.4nm;

Figure 6 shows maximum R_{ps} (at $\phi = 45^\circ$) as a function of groove depth;

Figure 7 shows a straight line fit to equation 1;

Figures 8a and 8b show alternative embodiments of the invention for use as a gas detector;

Figure 9 illustrates the use of a long range surface plasmon in gas chromatography;

Figure 10 shows an SPP-based voltage-controlled monochromator;

Figure 11 shows an alternative form of voltage-controlled monochromator;
 Figure 12 is an optical reader for magnetic tape.
 Figure 13 is a graph showing results of measurements taken with the apparatus of Figure 3; and
 Figures 14 to 22 are graphical depictions of further experimental results

Gratings were produced using a holographic technique. Clean glass discs were spin-coated with photoresist (Shipley 1400-17) and baked at 60°C for 30 minutes. These coated discs were then exposed to two intersecting coherent beams from an argon ion laser (457.9nm) for a range of exposure times. After exposure the films were developed, rinsed and left under an ultra-violet lamp for 30 minutes to harden the photoresist fully. Groove depths were subsequently measured using a Talystep stylus measuring instrument.

Such gratings were stored in a clean environment until, when needed, they were placed in a vacuum chamber for coating with an appropriate metal layer. Opaque silver layers of about 100nm thickness were deposited by evaporation of 99.999% pure silver in a vacuum of 10^{-4} Pa. The pitch, λ_g , of the gratings used was determined by the angles of the diffracted orders, and in all the gratings used here was 842.5 ± 0.5 nm.

The experimental arrangement used to monitor the reflecting properties of these metallised gratings is shown schematically in Figure 1. Gratings G were mounted on a table (not shown) that allowed angle (θ) scans having 0.01° step resolution. The azimuthal angle ϕ could be set to an accuracy of $\pm 0.1^\circ$. P-polarised (TM) HeNe laser radiation L ($\lambda = 632.8$ nm) was mechanically chopped at 1.7KHz and then directed on to the grating through a beam splitter BS and polariser P1. The zeroth order (specular beam) from the grating G was detected with a photodiode (rotating at twice the rate of the grating) and a lock-in amplifier after passing through a second polariser P2 set to pass the s-component of the beam. The extinction ratio of the two polarisers was greater than 200,000:1. A reference detector RD monitored the input beam through a 4% reflection off a glass plate beam splitter BS placed in the beam. This reference signal was used to correct the output signal for any fluctuations in input intensity. R_{ps} was measured as a function of θ with the scans being repeated for different ϕ values. Absolute magnitudes of R_{ps} were obtained by measuring the input beam with the signal detector set for p-polarisation. To reduce the influence of overlayer contamination of the Ag film the reflectivity measurements were conducted within 30 minutes of the deposition of the silver.

Figure 2 shows a practical embodiment of the apparatus. A CW laser diode 20 acts as a radiation source for an input beam IB which passes through a TM 21 polariser and is focused on to a grating 22 by a glass lens 23 which serves as a window to a sample chamber 24. An output beam OB passes through the lens L and a TE polariser 25 to a split detector 26 which resolves the angular position of the maximum. The grating pitch is designed to give SPP at $\sim 10^\circ$ incidence.

Figure 3 is another form of apparatus, using a light-emitting diode 30 in place of the laser of Figure 2. The wavelength spread of the LED is $\approx \pm 50$ nm. The detector 36 is a split λ detector with two diodes of different λ response. The output is very linear in position of λ maximum. The grating pitch is designed to give SPP at $\sim 10^\circ$ incidence.

Figure 13 shows results taken with the apparatus of Figure 3. When small amounts of isopropanol (< 1 Torr) are added to the chamber, condensation occurs on the metal surface and causes a change in the output of the wavelength detector. Pumping out the chamber re-evaporates the liquid and so returns the surface to its starting conditions.

Reflectivity data in the form R_{ps} against ϕ were recorded for ten different gratings, each with the same pitch but having different groove depths. Figure 4 illustrates the results recorded, this particular set of data is for a grating with a groove depth of 55.4nm. For $\phi = 0^\circ$ and 90° , i.e. grooves perpendicular or parallel to the plane of incidence, there is no detected R_{ps} . For all intermediate ϕ values there is a resonance peak at an angle of incidence which corresponds to the excitation of a surface plasmon, θ_{spp} . The movement of θ_{spp} with ϕ is clearly visible. Figure 5 shows the variation of the R_{ps} peak height with ϕ . The maximum p to s conversion occurs at $\phi = 45^\circ$ with, for this grating, almost 45% of the p radiation being converted through SPP absorption and re-radiation into s radiation. The dependent data closely follows a simple $\sin^2\phi \cdot \cos^2\phi$ ($= \sin^2 2\phi$) solid line dependence which is readily explained in terms of the electric-field components. P-polarised incident radiation has an E-vector component perpendicular to the grooves which varies as $\cos\phi$. This in turn has a component perpendicular to the incident vector which varies as $\sin\phi$. The product of these components is then squared to give the intensity.

For all the gratings the maximum R_{ps} at $\phi = 45^\circ$ was determined and the results, plotted against the square of the groove depth, are shown in Figure 6. The maximum conversion recorded was about 66% from a grating with an amplitude of 94.7nm. (By contrast, a polariser placed at angle ϕ between two crossed polarisers gives a maximum 12.5% conversion having likewise a $\sin^2 2\phi$ intensity dependence). The solid line shown in Figure 6 is a curve of the form;

$$R_{ps}(\max) = A[1 - \exp(-Bh^2)]^2. \quad (1)$$

The coefficients A and B are determined to be $2/3$ and $(251 \pm 10)/\lambda^2$ respectively (B is indistinguishable from

$8\pi^3/\lambda^2$). The straight line fit of $\ln(1 - (R_{ps}/A)^{1/2})$ against $(h/\lambda)^2$ for these values of A and B is shown in Figure 7.

In measurements of p to s conversion through the coupling of radiation to an SPP wave on a metallised grating, the dependence of the conversion efficiency on the groove depth and on the angle between the grating groove direction and the plane of incidence both take a very simple empirical form with a maximum conversion efficiency of 2/3 for the deepest grating.

The grating, by SPP conversion, is acting as a specular monochromator, that is if p-polarised parallel white light is shone on to the grating (at $\phi = 45^\circ$) the reflected beam when viewed through a second polariser will have a colour depending purely on θ . The narrower the SPP resonance the sharper the wavelength resolution in the output beam, the colour being dictated by that of the SPP mode on the metal surface. However to give strong conversion it is necessary to use a large groove depth which substantially broadens the SPP resonance and thereby limits the resolution.

Guided modes in a dielectric overlayer will also couple p to s on a grating. Figure 8 shows R_{ps} data taken at $\phi = 45^\circ$. The sample is a silver coated grating similar to that used in the previous example (groove depth of 53.6nm) but with a thin layer of photoresist spun on the silver. The modes give significant p to s coupling and, by careful overlayer application, modes as narrow as 0.1° HHFW should be obtainable.

Two broad types of device may be based on the principle of the surface plasmon. These are;

(a) Devices based on momentum spread at fixed wavelength.

(b) Devices based on wavelength spread at fixed momentum.

For the former one needs a monochromatic source - possibly a laser diode, and a position sensor.

For the latter one needs a polychromatic source - possibly an LED, and a wavelength sensor (dual diode detector).

There are two further subdivisions into;

(1) Metallised gratings supporting surface plasmons.

(2) Gratings coated with a dielectric layer supporting guided modes.

The first category will be sensitive to thin overcoatings and may themselves be overcoated with sensing layers.

The second category will be sensitive to changes in the optical properties of the dielectric layers.

An embodiment of the invention which serves as a gas sensor is shown in Figures 9a and 9b. This comprises a substrate 90 having a grating coated with a layer of gold 91 bearing a Langmuir-Blodgett (LB) film 92. Gas G flows over the film. The grating is alternatively illuminated with an incident beam IB comprising monochromatic light with an angular spread (Figure 9a) or collimated polychromatic light. The device acts as a gas sensor due to absorption of gas by the LB film - this changes the SPP resonance which is detected.

The use of a long range surface plasmon (LRSP) in gas chromatography is shown in Figure 10. Gas enters porous layer 101 bearing a gold layer 102 and changes the dielectric constant ϵ locally. This is seen as an image in s detected signal.

Figure 11 shows one form of voltage-controlled monochromator based on an SPP. An incident beam IB of white light is directed on to a grating coated with a transparent indium-tin oxide layer 111. This in turn, bears a layer 112 of a voltage sensitive polymer which is coated with gold or silver 113. A voltage change across the polymer applied by a voltage source 114 will cause a change in dielectric constant ϵ which leads to a colour change in the s output. Conversion efficiency is of the order of 60%. Spectral resolution is dictated by collimation of beams and sharpness of resonance.

Figure 12 shows an alternative embodiment of a voltage-controlled monochromator, but uses a liquid crystal layer position between the surface plasmon grating and a glass plate 121 bearing an indium tin oxide layer and a silica layer 122 aligned as shown in Figure 12b.

Figure 13 shows an optical reader for magnetic information using an LRSP comprising a silica substrate 130 and a gold grating overlayer 131 with a magnetic overlayer 132. The field from a tape 133 realigns magnetic overlayer and changes the LRSP. Hence magnetic information is converted directly to optical information. A plastic coating 134 for the magnetic overlayer acts as spacer and lubricant for tape flow.

Conversion of p to s radiation can also occur via guided modes in dielectric overlayers on a metallised grating. Figure 14 shows R_{pp} and R_{ss} reflectivities (at $\phi = 0$) from a sample consisting of 320nm of magnesium fluoride on 100nm of silver, evaporated under the same vacuum on to a grating (pitch = 801.5nm, depth = 21.1nm). The R_{pp} plot shows the SPP (at $\sim 42^\circ$) and the TM_0 (lowest order transverse magnetic) guided mode (at $\sim 13^\circ$). The guided mode is narrower the SPP as most of its field is in the non-absorbing dielectric. The R_{ss} plot shows the TE_0 guided mode.

If the grating is rotated to $\phi = 45^\circ$, we obtain the R_{sp} plot shown in Figure 15. The guided modes show much bigger mixing than the SPP. All the modes have moved to a higher angle in a similar way to the SPP in Figure 4. By measuring the peak height for the guided modes for $\phi = 0^\circ$ to 90° we obtain the curves in Figure 16. These curves for the guided modes differ from Figure 5 (for the SPP) in two important respects. The maximum of

each curve is now at $\phi > 45^\circ$ and they are both non-zero at $\phi = 90^\circ$. The same layers were also deposited on two other gratings of identical pitch but different groove depths. Table 1 shows the peak heights for the two guided modes and also the SPP for all three gratings at $\phi = 45^\circ$. (For the guided modes, this is not the optimal ϕ). The SPP mixing is compatible with the previous results for gratings coated only with silver.

These results show that guided modes give much larger mixing than SPPs especially for small groove depths. They are also narrower and hence will allow greater sensitivity in detecting mode shifts. With a dielectric coating on a metallised grating, the detectors shown in Figures 2 and 3 would now be sensitive to refractive index and thickness changes in the coating. The choice of layer would determine what materials are sensed. For example, layers exist that are only sensitive to specific gases and antibody layers exist that will only combine with the corresponding antigens. In both cases mainly the refractive index of the layer is modified.

TABLE 1
Mixing at 45°

Groove depth (nm)	TM ₀	TE ₀	SPP
211	0.115	0.326	0.033
376	0.359	0.496	0.159
719	0.508	0.559	0.277

Claims

- Optical sensing apparatus characterised in that it incorporates surface plasmon-polariton means for converting radiation between s and p modes together with means for detecting a maximum in conversion between said modes.
- Optical sensing apparatus as claimed in claim 1 characterised in that the means for converting radiation between s and p modes is a guided mode.
- Optical sensing apparatus as claimed in claim 1 characterised in that it includes means 21 for polarising incident radiation in a first plane grating means 22 orientated substantially at 45° with respect to the plane of incidence and crossed output polariser means 25.
- Optical sensing apparatus as claimed in claim 1 characterised in that it incorporates modulator means for modulating the frequency of the incident radiation together with detector means sensitive to said modulated radiation.
- A gas sensor incorporating an optical device as claimed in claim 1 characterised in that it comprises a substrate 90 having a grating coated with a layer of gold 91 bearing a Langmuir-Blodgett (LB) film 92.
- A detector for use in gas chromatography incorporating an optical device as claimed in claim 1 characterised in that it includes a porous layer 101 bearing a gold layer 102 together with means for detecting an image due to local changes in the dielectric constant of said porous layer.
- A voltage-controlled monochromator incorporating an optical device as claimed in claim 1 characterised in that it includes means for directing an incident beam IB of white light on to a grating coated with a transparent indium-tin oxide layer 111, a layer 112 of a voltage sensitive material coated with metal 113.
- A voltage-controlled monochromator incorporating an optical device as claimed in claim 1 characterised

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- A gas sensor incorporating an optical device as claimed in claim 1 characterised in that it comprises a substrate 90 having a grating coated with a layer of gold 91 bearing a Langmuir-Blodgett (LB) film 92.
- A detector for use in gas chromatography incorporating an optical device as claimed in claim 1 characterised in that it includes a porous layer 101 bearing a gold layer 102 together with means for detecting an image due to local changes in the dielectric constant of said porous layer.
- A voltage-controlled monochromator incorporating an optical device as claimed in claim 1 characterised in that it includes means for directing an incident beam 1B of white light on to a grating coated with a transparent indium-tin oxide layer 111, a layer 112 of a voltage sensitive material coated with metal 113.
- A voltage-controlled monochromator incorporating an optical device as claimed in claim 1 characterised



in that it includes liquid crystal means positioned between a surface plasmon grating and a glass plate 121 bearing an indium tin oxide layer and a silica layer 122.

- 5 9. An optical reader for magnetic information incorporating an optical device as claimed in claim 1 characterised in that it comprises a silica substrate 130 and a gold grating overlayer 131 with a magnetic overlayer 132.
- 10 10. A detector incorporating an optical device as claimed in claim 1 and means for selectively absorbing an entity to be detected characterised in that said means for selectively absorbing said entity changes its index of refraction as said entity is absorbed.

Patentansprüche

- 15 1. Optischer Sensor, gekennzeichnet durch eine Oberflächenplasmonen-Polaritoneneinrichtung zur Strahlungsumwandlung von s- und p-Moden und eine Einrichtung zum Ermitteln eines Maximums bei der Umwandlung zwischen diesen Moden.
- 20 2. Optischer Sensor gemäß Anspruch 1, dadurch gekennzeichnet, daß die Einrichtung zum Umwandeln der Strahlung zwischen den s- und p-Moden eine geführte Mode ist.
- 25 3. Optischer Sensor gemäß Anspruch 1, dadurch gekennzeichnet, daß eine Einrichtung (21) zum Polarisieren einfallender Strahlung in einer ersten Ebene, eine Gitter-Einrichtung (22), die im wesentlichen unter einem Winkel von 45° in Bezug auf die Einfallsebene ausgerichtet ist, und eine gekreuzte Ausgangspolarisationseinrichtung (25) vorgesehen sind.
- 30 4. Optischer Sensor gemäß Anspruch 1, dadurch gekennzeichnet, daß eine Modulationseinrichtung vorgesehen ist zum Modulieren der Frequenz der einfallenden Strahlung, zusammen mit einer Detektoreinrichtung, die für die modulierte Strahlung empfindlich ist.
- 35 5. Gassensor mit einer optischen Einrichtung gemäß Anspruch 1, dadurch gekennzeichnet, daß er ein Substrat (90) aufweist mit einem Gitter, das mit einer Lage aus Gold (91) beschichtet ist, die einen Langmuir-Blodgett (LB)-Film (92) trägt.
- 40 6. Detektor zur Verwendung in der Gaschromatografie, unter Verwendung einer optischen Einrichtung gemäß Anspruch 1, dadurch gekennzeichnet, daß er eine poröse Schicht (101) aufweist, die eine Goldschicht (102) trägt, zusammen mit einer Einrichtung zum Detektieren eines Bildes, das auf lokale Änderungen der Dielektrizitätskonstanten der genannten porösen Schicht zurückgeht.
- 45 7. Spannungsgesteuerter Monochromator mit einer optischen Einrichtung gemäß Anspruch 1, dadurch gekennzeichnet, daß er eine Einrichtung aufweist zum Richten eines einfallenden Strahls (1B) weißen Lichtes auf ein Gitter, das mit einer transparenten Indium-Zinnoxidschicht (111) beschichtet ist, eine Schicht (112) aus spannungsempfindlichem Material, das mit Metall (113) beschichtet ist.
- 50 8. Spannungsgesteuerter Monochromator mit einer optischen Einrichtung gemäß Anspruch 1, dadurch gekennzeichnet, daß er eine Flüssigkristalleinrichtung aufweist, die zwischen einem Oberflächenplasmonengitter und einer Glasplatte (121), die eine Indium-Zinnoxidschicht und eine Siliciumoxidschicht (122) trägt, angeordnet ist.
- 55 9. Optischer Leser für magnetische Informationen mit einer optischen Einrichtung gemäß Anspruch 1, dadurch gekennzeichnet, daß er ein Siliciumoxid-Substrat (130) und eine Gold-Gitterschicht (131) mit einer magnetischen Oberschicht (132) aufweist.



10. Detektor mit einer optischen Einrichtung gemäß Anspruch 1 und einer Einrichtung zum selektiven Absorben einer zu messenden Größe, dadurch gekennzeichnet, daß die genannte Einrichtung zum selektiven Absorben der Größe ihren Brechungsindex beim Absorbieren der Größe ändert.

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Revendications

1. Dispositif de détection optique, caractérisé en ce qu'il comprend des moyens formant polariton-plasmon de surface pour convertir un rayonnement entre des modes s et p, ainsi que des moyens pour détecter un maximum de conversion entre lesdits modes.
2. Dispositif de détection optique selon la revendication 1, caractérisé en ce que les moyens pour convertir un rayonnement entre les modes s et p sont un mode guidé.
3. Dispositif de détection optique selon la revendication 1, caractérisé en ce qu'il comporte des moyens (21) pour polariser un rayonnement incident dans des moyens formant réseau de diffraction d'un premier plan (22) orientés sensiblement de 45° par rapport au plan d'incidence et des moyens formant polariseur de sortie croisé (25).
4. Dispositif de détection optique selon la revendication 1, caractérisé en ce qu'il comprend des moyens formant modulateur pour moduler la fréquence du rayonnement incident, ainsi que des moyens formant détecteur sensibles audit rayonnement modulé.
5. Détecteur de gaz comprenant un dispositif optique selon la revendication 1, caractérisé en ce qu'il comprend un substrat (90) possédant un réseau de diffraction revêtu d'une couche d'or (91) portant un film de Langmuir-Blodgett (LB) (92).
6. Détecteur destiné à être utilisé en chromatographie gazeuse, comprenant un dispositif optique selon la revendication 1, caractérisé en ce qu'il comporte une couche poreuse (101) supportant une couche d'or (102), ainsi que des moyens pour détecter une image due à des changements locaux de la constante diélectrique de ladite couche poreuse.
7. Monochromateur commandé en tension comprenant un dispositif optique selon la revendication 1, caractérisé en ce qu'il comprend des moyens pour diriger un faisceau incident (IB) de lumière blanche sur un réseau de diffraction revêtu d'une couche transparente d'oxyde d'étain-indium (111), et d'une couche (112) d'un matériau sensible à la tension revêtu de métal (113).
8. Monochromateur commandé en tension comprenant un dispositif optique selon la revendication 1, caractérisé en ce qu'il comprend des moyens à cristaux liquides positionnés entre un réseau de diffraction de plasmon de surface et une plaque de verre (121) supportant une couche d'oxyde d'étain-indium et une couche de silice (122).
9. Lecteur optique destiné à l'information magnétique comprenant un dispositif optique selon la revendication 1, caractérisé en ce qu'il comprend un substrat de silice (130) et une couche de recouvrement de réseau de diffraction en or (131), ainsi qu'une couche de recouvrement magnétique (132).
10. Détecteur comprenant un dispositif optique selon la revendication 1 et des moyens pour absorber sélectivement une entité devant être détectée, caractérisé en ce que lesdits moyens pour absorber sélectivement ladite entité changent d'indice de réfraction pendant que ladite entité est absorbée.

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