Abstract.

The characteristics of surface plasmon light modulators are compared with those of other structures used in SLM's, in order to investigate the possible response uniformity advantages offered by the thin, single surface nature of the surface plasmon resonance effect. Detailed comparison is made with fractional waveplate structures for liquid crystal based devices, and with Fabry-perot structures for semiconductor devices. The critical device fabrication technologies, dimensions, and required tolerances are described in each case and judged in the light of current SLM performance requirements.

1. Introduction.

The small size of many electro-optic (EO) effects means that optical modulators typically require large optical path lengths, but this becomes impractical in SLM devices, where large numbers of beam paths need to be modulated in parallel and with a high spatial resolution. Liquid crystal EO materials are a notable exception, having a large EO effect and finding application in thin SLM structures (=2µm). For lower sensitivity materials such as semiconductors, the size of modulation obtained may be increased by placing the material in an optically resonant structure, usually a Fabry-perot cavity, to enhance the optical field, and again allow a thin device structure to be made. Another type of system which may be used in this way is a resonantly excited guided mode, and in this case the mode propagation length places a fundamental limit on the spatial resolution which may be obtained. A mode with a propagation length suitably short for spatial light modulation is the surface plasmon mode, which is a classical electromagnetic wave associated with longitudinal charge oscillations on the interface between a metal and the EO material. This guided wave is relatively lossy since much of the field lies in a metal, and it has a typical propagation length in the order of 20µm. This is sufficiently short to allow two-dimensional spatial light modulation to be obtained at a high resolution of > 10 lp/mm [1].

Another important SLM performance parameter is the response non-uniformity which occurs, since this limits the contrast and grey level capability of the device. This parameter is difficult to characterise or compare between devices, as it is dependent on material and processes and their quality control. It may however be split into two parts: that due to variations in material EO properties, and that due to thickness variations in the structure. The latter contribution is more characteristic of the particular device structure, and will be that analysed quantitatively here. In surface plasmon and Fabry-Perot SLM's with resonant field enhancement, the sensitivity to non-uniformities in the device is enhanced by a similar degree to the EO sensitivity, and so a sensitivity/uniformity trade-off arises with varying resonant quality factor.

As well as the suitable spatial resolution capability, another feature of the surface plasmon modulator structure which makes it attractive for SLM applications is the single interface nature of the waveguide. That is, the light modulation occurs within a thin (=0.2µm) evanescent field region which is supported by and bound to the metal surface. The response is therefore relatively immune to any thickness variations in the EO layer. In each structural type of modulator, one particular thickness dimension is critical for response uniformity. For both Fabry-Perot and waveplate type devices this thickness is that of the EO layer (cavity or LC thickness respectively). In the plasmon device, however, due to the evanescent field structure the critical dimension is that of the coupler - either the metal film thickness or the grating depth, in prism- or grating-coupled devices respectively.

Two types of thickness non-uniformity effects can be identified; for large full-frame contrast (Cff), control of device dimensions is required in fabrication to achieve a uniform dark state, but no dependence on EO sensitivity arises. For large grey-level number (G) however, the uniformity required will depend also on the EO sensitivity, and the nature of the EO mechanism involved. The separate contributions of variations Ad to contrast ratio in the un-addressed state, and to grey level number in the addressed state, will be termed as "contrast ratio" and "EO" non-uniformity contributions.

2. Choice of sensitivity and uniformity criteria.

The measure of thickness non-uniformity chosen is the variation Ad in the thickness d which causes a variation in modulator output, in terms of either reflection or transmission intensity coefficient, of 0.01, and this is denoted Ad0.01. For devices which exhibit high contrast light modulation with low insertion loss, i.e. devices which can modulate R or T between approximately 0 and 1.0, such a non-uniformity would allow about G=100 grey-levels, and a similar full-frame contrast ratio Cff, to be obtained. This figure is chosen as a reasonable representation of...
device requirements in applications such as large volume interconnects, and a reasonable target figure for current manufacturing technology.

The measure of device sensitivity is chosen as the electro-optic modulation which increases the modulator signal, in terms of reflection coefficient, from the dark state $R=0$ up to 0.5. This sensitivity parameter will be a change either in refractive index, or device bias voltage, and it is denoted by a subscript "0.5"; for example $\Delta V_{0.5}$.

These thickness and sensitivity parameters are now determined for various modulator structures.

3. Surface plasmon SLM devices

The reflectivity of a surface plasmon resonance device is given by [2]

$$R(\beta) = 1 - \frac{4\Gamma \sin \theta}{(\beta - \beta_p)^2 + (\Gamma + \Gamma_p)^2}$$

(1)

where the component of the light wavevector parallel to the plasmon surface is $\beta = n_p \sin \theta$, $n_p$ is the coupling prism refractive index, and $\theta$ is the angle of incidence. The resonance occurs at $\beta=\beta_p$, $\Gamma_p$ is the ohmic loss of the plasmons and $\Gamma_0$ is the radiative loss, which is also a measure of the coupling strength. In prism coupling, this may be controlled via the metal thickness, and by setting $\Gamma_F = \Gamma_0$, from equation (1), a minimum reflectivity close to zero may be obtained at resonance, i.e. nearly 100% coupling efficiency is obtained. The quality factor of the resonance is then given by

$$Q = \frac{\beta_p}{4\Gamma_0}$$

(3)

In the surface plasmon spatial light modulator, local changes in the EO material index alter the plasmon propagation constant, and so change the position (or depth) of the SPR curve (equation 1) relative to the incident beam, so that local light modulation is produced on reflection (figure 1), allowing 2-D spatial light modulation to be obtained [3].

Thickness non-uniformity in the metal layer affects the response of an SPR modulator by altering the resonance angular position ($\beta_p$) and the coupling strength $\Gamma_0$, and in the weak-coupling analysis this occurs according to [4]

$$\Delta \beta + j\Gamma_0 = A \exp(-2\sqrt{\epsilon_r k d_m})$$

(4)

where $\epsilon_r$ is the absolute value of the real part of the metal dielectric constant and $A$ is a constant.

4. Grating-coupled surface plasmons

Grating-coupling is more attractive than prism-coupling because it allows smaller angles of incidence to be obtained, and hence increased aperture, and also higher refractive index EO materials to be used. In this case the SPR effect is more difficult to analyse. In devices reported to date, the metal layers have a large thickness $>100$nm, and this is effectively infinite for coupling purposes, so that no proximity coupling occurs. Instead the coupling mechanism is Bragg scattering, and coupling strength is controlled by the amplitude (i.e. depth) of the relief grating upon which the metal is deposited. Reference [5] includes a review of this field as well as the characterisation of grating-coupling of plasmons on silver/air interfaces at 633nm wavelength.

From reference [6], the value of $\Delta d_0/(d_0)$ is 5% for Ag/air plasmons at 633nm. For EO materials with larger refractive index, the higher loss (lower $Q$) will require larger coupling strength, i.e. deeper gratings, but the coupling will also be less sensitive to grating depth variations than in the silver/air case, due to the increased loss. These factors will tend to offset each other, and in the absence of better characterisation data, we take the uniformity figure of silver/air plasmons as representative of those for the other devices considered, i.e. $\Delta d_0/(d_0) = 5\%$ for all grating-coupled plasmons considered here.

5. LC based SPR modulators

Here the LC parameters will be taken as those of material E7 from BDH (Merck) Ltd [6], since this has been characterised previously in both waveplate and surface plasmon experiments [7,8] in homogeneous alignment. In the surface plasmon device the LC director modulation is in the plane parallel to the plane of incidence, and the sensitivity and uniformity parameters are calculated using the analysis of [8], and included in table 1.

For nematic LC the pinning action of the alignment layers reduces the EO distortion of the LC near the cell walls (figure 2). This leads to reduced sensitivity in the plasmon device, since here the active region is near the surface, as compared to the waveplate device, where the active region extends right through the LC layer. Because of this, and the nature of the nematic LC director profile, the voltage sensitivity in the plasmon devices is improved by
decreasing cell thickness, whereas in waveplate devices sensitivity is improved with increasing thickness (table 1).

6. LC-based waveplate modulator.

Many waveplate SLM’s now use smectic LC materials for their increased speed. For example surface stabilised ferroelectric LC is used with a twist orientation $\psi$ which is switchable by an amount $\Delta \Phi = 45^\circ$, allowing full modulation e.g. from $R=0$ to $R=1$, with < 10 V bias. In SPR devices, however, twist modulation involves mixed polarisation effects [10] which are too complicated to consider in detail here. This discussion is therefore restricted to devices based on nematic LC type E7, in a homogeneous alignment, as in the plasmon device of section 5. In this waveplate device the readout beam is incident on a polariser, LC cell, mirror arrangement so that a double pass through the LC occurs giving readout in reflection. Maximum contrast is obtained with the LC alignment at 45$^\circ$ to the polariser, whereupon

$$ R = \cos^2 \Phi $$

(5)

where $\Phi$ is the net phase retardation produced between the fast and slow rays in the LC. At 0V bias a dark (R=0) state is obtained by setting the thickness equivalent to an odd integer number of quarter wavelengths, and $R$ is then increased by applying the bias voltage, which distorts the LC as in figure 2, thus decreasing $\Phi$. As for the SPR device two cases are considered; thin cells with $d_{WP}=2 \mu$m, and thick cells with $d_{WP}=10 \mu$m. By again using the LC analysis of reference [8], the sensitivity and uniformity parameters are found, and are included in table 1.

7. Semiconductor based SPR modulator.

For semiconductor SPR devices the high refractive index of $n\geq 3$ means that grating-coupling is essential. Also, the band-gap restrictions of common semiconductors leads to the requirement that near infra-red wavelengths must be used to avoid excessive absorption. However, due to the large dispersion of metals the plasmon loss is much reduced at longer wavelengths. For plasmons on typical silver/semiconductor systems in the near infra-red, these two effects tend to cancel each other, such that the net loss (Q), and sensitivity $\Delta \Phi_{0.5}$ or $\Delta \Phi_{0.5}$ is similar to that of the LC based devices at 633nm. Consequently the normalised grating uniformity parameter is also expected to be similar, at about $\Delta \Phi_{0.01}/d \approx 5 \%$. Here the best example is that shown in figure 3 [11], where plasmons on Ag/Si at 1.3 $\mu$m wavelength are modulated in a Schottky diode, using free-carrier electro-refraction under reverse bias breakdown conditions. Note that the Schottky contact is also the grating coupler in this device. The reported sensitivity and calculated uniformity parameters of this device are summarised in table 1.

Epitaxial semiconductor devices, for example using the EO effects obtainable in MQW’s, could also be used to achieve the required sensitivity $\Delta \Phi_{0.5}$ or $\Delta \Phi_{0.5}$. In this case, however, problems arise due to the requirement that the grating depth must be of comparable size to the active region thickness. The resulting proximity or even intersection between the grating surface and the MQW’s would undoubtedly cause materials related problems.

8. Semiconductor based Fabry-Perot modulator.

More commonly, semiconductor modulators take the form of Fabry-Perot cavities, which have the advantages of all-planar geometry, and controllable resonant sensitivity enhancement. In this case for simplicity any thickness variations in the MQW’s are regarded as materials non-uniformities. The exact structure of the cavity reflectors, for example whether they are distributed, are also ignored, and the important thickness for uniformity is that of the cavity, $d_{FP}$. As in SPR devices, there is a trade-off between uniformity and sensitivity, with the accuracy $\Delta d_{0.5}$ with which the thickness control and uniformity must be achieved, decreases with increasing quality factor (sensitivity).

The example considered here is the asymmetric Fabry-Perot device structure, which allows high contrast modulation to be obtained, as required for SLM applications, using electro-absorption to create a null-point in the reflectivity-versus-voltage characteristic [12]. If the front and back cavity mirrors have reflectivities $R_f$ and $R_b$ respectively, the net reflectivity is given by [13]

$$ R = 1 - \frac{1 + R_f^2 - R_b - R e^{-2d_{FP}}}{(1 - R_f)^2 + 4R_b sin^2 \Phi} $$

(6)

where

$$ R_b = \sqrt{R_f R_{res}^{e^{-2d_{FP}}}} $$

and the quality factor is

\[ \text{Quality Factor} \]

5/3
\[ Q = \frac{k_n \alpha}{1 - \log_e (\sqrt{R_F R_B})} \]  

(7)

The AFT typically has \( R_F = 0.3 \) and \( R_B = 0.95 \). The \( R = 0 \) dark state occurs at an induced absorption in the order of \( \Delta \alpha = 10^5 \text{cm}^{-1} \), and has \( Q = 50 \). The refractive index sensitivity and uniformity parameter \( \Delta d/\alpha \) for this dark state are calculated using equation (6). A large electro-absorption effect is attainable with MQW excitonic effects, giving a voltage sensitivity of \( \Delta V_{0.5} = 10 \text{V} \) [12]. These characteristics are also included in table 1.

9. Comparison of modulator types and conclusion.

The table shows that each modulator has a similar net sensitivity, in terms of the order of magnitude of \( \Delta V_{0.5} \). In the LC waveplate device the index sensitivity is low, but this is offset by the exceptionally high material sensitivity, to give a very high voltage sensitivity. In the SPR device however, this high LC sensitivity is not exploited as efficiently, due to the reduction in LC modulation near the cell surface (figure 2), and consequently the voltage sensitivity is poorer.

The table also shows the large structural differences between the modulator types, with the scale of the critical dimension being very different in each case, both in size and in fabrication method. For the SPR devices, this dimension, of either metal thickness or grating depth, is much smaller than those of the other two device types, both of which are EO layer thicknesses, and for full frame contrast this leads to a uniformity advantage for SPR in terms of fractional thickness variations i.e. \( \Delta d/d \). Much will actually depend on the relative capabilities of each of the very different fabrication technologies to meet the stated uniformity criteria, but it is likely that better control and uniformity can more easily be achieved in thinner layers.

In terms of the EO uniformity requirements for grey level number, however, the expected uniformity advantage of the SPR device is much smaller (< a factor of 2) for both LC and semiconductor devices. This is because at the thin LC cell thickness (= 2\mu m) or thin semiconductor depletion region (= 1\mu m), which must be chosen to give the SPR device high sensitivity, the ratio \( \Delta d/d \), and its effect on the EO sensitivity, is relatively large. This is to be expected, since by choosing the cell thickness to be small enough to give comparable sensitivity between SPR and waveplate devices, comparable EO non-uniformity characteristics should also be obtained. The thickness immunity characteristics of the evanescent field active region in the SPR device are therefore best exploited by using an EO layer thickness much larger than the evanescent field depth, providing the EO material sensitivity will allow.

To conclude, the SPR modulator structure does offer a potential uniformity advantage in terms of achieving a large full-frame contrast ratio, although the realisation of this will depend on relative technical factors. This is especially true for grating-coupled SPR on semiconductors, which is still at an early stage of development. For grey-level number in EO response, at equivalent net voltage sensitivities (i.e. similar EO layer thickness), in semiconductor Fabry-Perot, LC waveplate and SPR devices, the latter has only a minor thickness uniformity advantage.

References

6. LC data sheet BDH (Merck) Advanced Materials, Broome Rd, Poole. Dorset.
11. A. F. Evans and D. G. Hall "Measurement of the electrically induced refractive index change in silicon for

Table 1. Comparison of sensitivity and thickness uniformity properties of modulators.

<table>
<thead>
<tr>
<th>Critical thickness parameter</th>
<th>SPR Ag/LC at 633nm</th>
<th>Ag/Si at 1300nm</th>
<th>Fabry-Perot at 1500nm Asymmetric</th>
<th>LC waveplate at 633nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality factor</td>
<td>50</td>
<td>100</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>Sensitivity Δρ1.5 Δκ0.5</td>
<td>(0.02)</td>
<td>0.02</td>
<td>0.017</td>
<td>(0.1)</td>
</tr>
<tr>
<td>ΔV0.5</td>
<td>2.5V (2μm)</td>
<td>3V</td>
<td>10V</td>
<td>&lt;1.3V</td>
</tr>
<tr>
<td>Critical layers and dimensions</td>
<td>Silver ~60nm</td>
<td></td>
<td>Cavity thickness ~ 5nm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Align't Grating layer depth ~25nm =300nm</td>
<td></td>
<td>LC cell thickness ~ 2μm</td>
<td></td>
</tr>
<tr>
<td>Critical fabrication steps</td>
<td>Thin film Grating deposition etch</td>
<td>MBE growth &gt; 20 layers</td>
<td>2μm glass cell assembly</td>
<td></td>
</tr>
<tr>
<td>Thickness control method</td>
<td>For Cff &gt; 100</td>
<td>&lt;±2.5nm (5%)</td>
<td>&lt;±15nm (5%)</td>
<td>&lt;±50nm (2.5%)</td>
</tr>
<tr>
<td></td>
<td>in 2μm LC</td>
<td>&lt;±5nm (0.3%)</td>
<td>&lt;±5nm (0.3%)</td>
<td>&lt;±3nm (0.15%)</td>
</tr>
<tr>
<td></td>
<td>in 10μm LC</td>
<td></td>
<td>in 2μm LC</td>
<td>&lt;±5nm (0.25%)</td>
</tr>
<tr>
<td></td>
<td>in 10μm LC</td>
<td></td>
<td>in 10μm LC</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Prism-coupled surface plasmon SLM structure.

Figure 2. Modal field structure and typical director profile for nematic LC in the SPR device.

Figure 3. Silicon surface plasmon modulator