Surface-plasmon spatial light modulators based on liquid crystal

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The development of a new class of spatial light modulator (SLM), which uses modulation of lossy guided waves generated by surface-plasmon resonance, is described. The potential advantages of this technique are explained, including increased response uniformity and enhanced sensitivity and speed. An optically addressed SLM that is based on a nematic liquid crystal with a spatial resolution better than 10 line pairs/mm (at 50% modulation transfer function) is demonstrated. For the design of devices that are based on newer smectic liquid crystals the use of anisotropy-induced polarization mixing and the so-called pseudoplasmon modes are described. Such modes offer controllable sensitivity–spatial resolution characteristics in simple liquid-crystal SLM structures. Within a typical SLM resolution requirement of 10 line pairs/mm, for example, the sensitivity can be optimized to obtain a theoretical reflectivity modulation from 0 to 0.7 for a liquid-crystal director modulation of 5°.

Key words: Guided-wave modulators, surface-plasmon resonance, optically addressed spatial light modulators, pseudoplasmons, liquid crystal.

I. Introduction

The development of optical modulators has been hampered by the fact that electro-optic (EO) effects that are used tend to be weak in high-speed devices such as semiconductors while large effects are obtainable only in slower materials such as liquid crystals (LC’s). One way to enhance the degree of light modulation that is obtainable from a given EO effect is to use the active material in an optically resonant structure such as a Fabry–Perot étalon; this effectively folds the optical path many times through the material and multiplies the sensitivity, in terms of phase shift or absorption, accordingly.

Another structure that can be used in this way is a resonantly excited guided mode. Such a mode can be excited by a prism (or grating) coupler by means of the interaction between the mode and the evanescent field of a totally internally reflected incident beam. The field intensity in the guide can then be much higher than that of the incident beam and, if the mode propagates in some active material, the modulation of the incident beam can be enhanced accordingly. The degree of enhancement increases with decreasing mode loss, i.e., increasing mode propagation length and, consequently, a sensitivity–spatial resolution trade-off occurs. Additionally the higher sensitivity of lower-loss modes to EO effects is accompanied by a similarly high sensitivity to any nonuniformity in thickness or optical properties of the device. High spatial resolution and response uniformity are both of prime importance in spatial light modulator (SLM) applications and so in this case the guided mode that is used must be chosen carefully for its sensitivity, resolution, and uniformity properties.

The mode that we have chosen to exploit is the surface plasmon. This surface mode, being supported by a single interface, has the potential for high response uniformity in large-aperture devices. It propagates on the surface of a metal and so is relatively lossy with a short propagation length (≈ 20 μm), which is suitable for use in high-resolution SLM’s. Furthermore in certain cases the loss can be controlled in order to optimize the guided-mode sensitivity–resolution trade-off to the particular SLM application.

In Section II we describe the surface-plasmon resonance (SPR) technique and briefly review previously reported SPR modulator devices. Section III explains the suitability and attractive features of this technique for SLM applications as well as their disadvantages. In Section IV we detail our experimental work in this area, which involves the demonstration of a nematic LC-based device as an image con-
Section V is concerned with the design of higher-performance devices based on the newer smectic LC materials. Such devices utilize polarization mixing effects and, in particular, the so-called pseudo-plasmon modes.

II. Surface-Plasmon Spatial Light Modulation

Surface plasmons are longitudinal charge-density waves that can be excited at optical frequencies on the surface of a conductor. The associated electromagnetic fields constitute a guided surface mode of the conductor–dielectric interface and are evanescent in each medium with intensity decaying exponentially away from the interface. If the dielectric is isotropic the mode has transverse-magnetic (TM) polarization.

The excitation of surface plasmons by prism coupling has been widely reported. In the configuration employed here, which is shown in Fig. 1(a), an incident TM-polarized beam undergoes total internal reflection at the prism base, generating an evanescent field that extends through the thin metal film to couple to the plasmon mode on its lower surface.

The excitation of plasmons is a resonant process, as illustrated in Fig. 1(b), which shows the dip in reflected intensity that occurs as the angle of incidence is scanned past the optimum coupling angle \( \theta_r \). The dip in reflectivity occurs as the plasmons are resonantly excited by, and absorb, the incident beam, and the phenomenon is known as SPR. The field intensity in the structure is also shown in Fig. 1(b) for three angles of incidence to illustrate how the plasmon field in the dielectric is enhanced, and the reflected field suppressed, near resonance.

For analyzing this process the component of the incident-beam wave vector in the direction parallel to the film is denoted by \( \beta \); it is related to the angle of incidence \( \theta \) by

\[
k_o n_p \sin \theta = \beta,
\]

where \( n_p \) is the index of the coupling prism and \( k_o \) is the optical wave vector in free space. At resonance we have

\[
k_o n_p \sin \theta_r = \beta_r,
\]

where \( \beta_r \) is the real part of the plasmon propagation constant and the imaginary part is denoted by \( \Gamma_r \). For prism coupling of low-loss surface plasmons such that \( \Gamma_r \ll \beta, \beta_r \) is given approximately by the dispersion relation of plasmons on a semi-infinite metal layer:

\[
\beta_r + j \Gamma_r = k_o \left( \frac{\varepsilon_m \varepsilon_d}{\varepsilon_d + \varepsilon_m} \right)^{1/2}.
\]

Here \( \varepsilon_m \) and \( \varepsilon_d \) are dielectric constants of the metal and the dielectric, and \( \Gamma_r \) arises from ohmic losses in the metal. On the thin-film structure in the absence of excitation the plasmon field \( H \) decays with distance \( z \) as

\[
H(z) = H(0) \exp\left[-(\beta_r + \Gamma_r)z\right],
\]

\[
\Gamma_r = (\Gamma_1 + \Gamma_r).
\]

\( \Gamma_r \) represents the additional loss that is due to the finite metal film thickness, which occurs through reradiation of the plasmon field back into the prism. With this formalism the reflection coefficient \( r(\beta) \) in the SPR experiment can be written as

\[
r(\beta) = \frac{1 - 4\Gamma_r^2}{(\beta - \beta_r)^2 + (\Gamma_1 + \Gamma_r)^2},
\]

where \( r_{pm} \) is the reflection coefficient at the prism–metal boundary in the case of semi-infinite metal. The resulting intensity reflectivity \( R(\beta) \) is

\[
R(\beta) = 1 - \frac{4\Gamma_1 \Gamma_r}{(\beta - \beta_r)^2 + (\Gamma_1 + \Gamma_r)^2},
\]

which is the Lorentzian dip shown in Fig. 2. As well as a phase-matching condition for resonance \( \beta = \beta_r \), an impedance-matching condition also exists, in which \( R(\beta) \) approaches zero at resonance (maximum coupling efficiency) if the two loss mechanisms give equal contributions, i.e.,

\[
\Gamma_1 = \Gamma_r.
\]

This loss-matching condition is achieved, in practice, by control of the metal film thickness. From Eq. (7) the reflectivity curve FWHM is then equal to \( 4\Gamma_1 \) and the quality factor \( Q \) is

\[
Q = \frac{\beta_r}{4\Gamma_1}.
\]

To obtain a large resonant enhancement of the
plasmon field a high-conductivity metal is used to give a small \( \Gamma_f \) and a high quality factor. Silver is the best metal at a 633-nm wavelength, in which Eq. (8) is satisfied for a thickness of \( \sim 50 \) nm. With air as the dielectric and \( n_{p} \approx 1.5 \) the angular width of the reflectivity dip is \( \sim 0.2° \). Enhancement of the field intensity at the plasmon interface over that of the incident beam is then \( \sim 2 \) orders of magnitude and a large proportion (> 95%) of the plasmon field energy lies in the dielectric, where it is available for sensing or modulation purposes when the dielectric is some active material. For EO dielectric materials such as LC's the larger refractive index causes more of the plasmon field to lie in the metal and so reduces the quality factor of the resonance (increasing \( \Gamma_f \)). For high-refractive-index materials such as semiconductors suitably high-index materials generally are not available for prism coupling, and so grating coupling is employed; it shows similar resonant behavior. At near-infrared wavelengths, which are required for many semiconductor modulators, Au gives a quality factor that is similar to Ag and also is easily deposited and chemically stable.

In the SLM configuration shown in Fig. 2 the EO material that forms the dielectric is in the form of a thin film, which should be greater than 0.2 \( \mu \text{m} \) thick to fully support the plasmon field. The film is made locally addressable; in the simplest case pixel electrodes are used for applying the modulating electric field. Induced changes in \( \varepsilon_{2} \) modulate \( \beta_{p} \), according to Eq. (3) and this locally shifts or otherwise distorts the reflectivity curve from Eq. (7). If the device is illuminated with an expanded, collimated, TM-polarized read beam at an angle near resonance, spatial light modulation will be obtained directly after reflection, as illustrated in Fig. 2.

Light modulation by SPR has been used for studying voltage-dependent alignment in nematic LC's under static equilibrium conditions and for more detailed investigations of new smectic LC materials. A fast, large-aperture piezoelectric modulator has been demonstrated while surface plasmons have also been investigated in the context of optical bistability. The use of surface plasmons in semiconductor modulators has been analyzed, and devices that are based on free-carrier refractive-index modulation in silicon Schottky diode structures have been demonstrated. Display devices that are based on electrochemical and Langmuir–Blodgett films have been patented while surface plasmons have also been used for microscopy of thin films with a lateral resolution approaching 20 \( \mu \text{m} \). We have demonstrated electrically addressed SLM devices based on nematic LC's that show similar spatial resolution and previously have discussed the promise of this class of SLM. The prism-coupled LC surface-plasmon SLM is related to the total internal reflection (TIR) LC switch and has a similar optical configuration (see Section V).

In all SPR modulator devices the contrast that is obtained is limited by the depth of the reflectivity curve, i.e., the degree of impedance matching that is obtained [Eq. (8)]. Because of the shape of the SPR reflectivity curve the response is generally nonlinear, although near-linear response may be obtained at reduced contrast by operating on one side of the SPR curve near the half-minimum point. Both the amplitude and phase of the reflected beam are always modulated, and this class of device has an amplitude-phase characteristic that is determined by Eq. (6). Modulation of the real part of the refractive index shifts the angular position of the SPR dip, while modulation of the imaginary part (the optical absorption) changes plasmon loss and hence the width and depth of the dip. In devices that utilize high birefringence, in LC's, for example, the plasmon field distribution and polarization can be significantly modulated, changing both position and width of the reflectivity curve. In each case a different amplitude-phase modulation characteristic is obtained.

### III. Attractive Features and Limitations of SPR in SLM Applications

#### A. Single-Surface Nature of the SPR Effect

The fact that, in surface-plasmon devices, light modulation is achieved directly by the interaction of the read beam with a thin film on a single interface suggests that it should be possible to achieve better response uniformity, particularly in terms of phase distortion, than in conventional SLM's. In these the read beam must be transmitted through several interfaces and it often encounters a multilayer reflector and also an output polarizer. In the present surface-plasmon device the read beam encounters all three faces of a coupling prism but in future grating coupled devices a metallized grating that supports the plasmons could be fabricated on an external surface of the device and so become the only surface that is encountered by the read beam. The phase distortion would then be limited mainly by the flatness of this surface and the uniformity of the metal film and metal–dielectric interface although, as in all devices, nonuniformity in EO material optical properties could also contribute. A similar uniformity advantage also applies to the TIR switch although, in this case, it applies to the reflecting state only, i.e., that in which the TIR of the incident beam occurs.

A single interface nature also means that, provided that the EO layer thickness is larger than that of the plasmon field region, the optical read and electrical write portions of the device are well separated. Consequently the light blocking or dielectric mirror layers that are needed to protect the photosensitive write portions of other SLM's are unnecessary. Similarly the read beam is unaffected by any topography that is present on the addressing backplane. This permits removal of the planarization layers that are usually required in LC devices with microcircuit backplanes; nematic LC's, for example, can be aligned directly onto such backplanes. These process simplifications have obvious attractions in terms of cost.

Another issue, which is related to that of back-
plane topography, is uniformity of response to an addressing signal. In most SLM's this is governed by variations in thickness of the EO material through two effects. First, the electric field from the constant addressing voltage varies across the device, varying the response of the EO material. Second, the optical path length of the read beam in the EO material also varies. Many bulk-effect modulators, such as quarter-wave plate devices, depend on the exact control of this path length and its uniformity for achieving high contrast and a maximum number of grey levels in the response. In the plasmon device, however, the response is relatively immune to any optical path-length variations in the EO layer. In fact the important optical path length in SPR modulation is the metal film thickness, since this controls the contrast by means of the reflectivity curve depth. For equivalent LC modulator structures, a variation in metal film thickness in the plasmon device of the order of 2 nm produces a similar response nonuniformity as a cell thickness variation in a quarter-wave plate device of the order of 0.1 μm. The realization of the potential uniformity advantage of surface-plasmon SLM's, therefore, depends on the relative capabilities of thin-film deposition and LC cell fabrication technologies of producing thickness uniformities within these scales. The ultimate contrast ratio capabilities of the two types of modulator structure similarly depend on the controllability of the absolute thickness values in these processes, although other factors such as material and polarization quality are also involved. We previously reported contrast ratios of > 100:1 in electrically addressed plasmon devices with a 5-mm aperture. The uniformity limitation of thin-film deposition appears to be of the order of 1 nm over a typical SLM aperture size of 2 cm and this corresponds to an ultimate contrast ratio limit of ~10^3 for surface-plasmon SLM's.

B. Thin Active Region and Device Sensitivity

In SPR modulators the EO active region is relatively thin, being confined to the evanescent field region within ~0.3 μm of the metal film, where it is enhanced considerably at resonance. We define the active region depth \( d_{act} \) as the 1/e decay depth of the evanescent field amplitude, and for an isotropic EO material this is given by the dispersion relation

\[
d_{act} = \frac{j}{(\varepsilon_0 k_0^2 - k_r^2)^{1/2}}. \tag{10}
\]

As an EO sensitivity parameter we choose the real refractive-index change that is required to modulate reflectivity \( R \) from 0 to 0.5 and this is denoted by \( \Delta n_{0.5} \). This is the change that shifts the SPR dip by its own HWHM, i.e., by 2 \( \Gamma_i \), and for \( \Gamma_i \ll \beta \), this is given by

\[
\Delta n_{0.5} = \frac{2\Gamma_i}{(d\beta_r/dn)}, \tag{11}
\]

Typically,

\[
\Delta n_{0.5 d_{act}} = \frac{\lambda}{2Q}. \tag{12}
\]

This product can be compared with that of a bulk-effect modulator, for example, a typical birefringent quarter-wave plate Pockels-effect device. In the case of the Pockels effect, an induced index difference \( \Delta n_{0.5} \) between the principal refractive indices acts over the film thickness \( d \) to produce a modulation of transmission (between crossed polarizers) from 0 to 0.5, when the retardation between the fast and slow rays equals an eighth wavelength, i.e.,

\[
\Delta n_{0.5 d} = \frac{\lambda}{8}. \tag{13}
\]

A comparison of approximation (12) and Eq. (13) indicates the sensitivity advantage of the plasmon device, which is due directly to the resonant field enhancement by a factor of \( Q \). The active region of the plasmon device is, however, much smaller than that of most devices, which have \( d > 2 \mu m \) by a similar amount, so that no real sensitivity advantage is obtained in terms of \( \Delta n_{0.5} \). Plasmon devices do, however, offer a clear sensitivity advantage for use with materials that (a) are obtainable in thin films only, e.g., Langmuir–Blodgett films, (b) have cost, uniformity, or addressing advantages when in thin films, e.g., semiconductor multiquantum well and depletion region structures, or (c) have speed advantages over bulk material when in thin-film form. The latter include chemical effect materials such as electrochromics and photochromics, whose response is often governed by diffusion processes, the speed of which is greatly enhanced in thinner structures.

In plasmon devices with EO layers that are thicker than ~0.3 μm, some material modulation is wasted in regions of low optical field. In LC devices, for example, with thicknesses that are typically larger than 2 μm, less than 10% of the cell is used. The nature of the LC surface region then may also reduce the sensitivity. In nematic LC's, for example, the tilt modulation is always much less near the cell surfaces than in the bulk because of the action of the aligning layers at these surfaces. The sensitivity also is reduced by the presence of the alignment layer itself, which therefore must be kept as thin as possible relative to \( d_{act} \) (we have used a typical thickness of 25 nm). Alignment layers also produce scattering losses, since by their nature they usually have some surface roughness and, in the case of evaporated layers, some porosity also. The widths of measured SPR dips are therefore always slightly larger than the ideal values that are calculated by using bulk material data because of these nonidealities in thin films, and so real plasmons must be characterized empirically. For the most studied case of plasmons in Ag/LC structures at a 633-nm wavelength measured SPR widths^6,7,17 are approximately 2°–3°, corresponding to \( \Gamma_i/k_0 \approx 5 \times 10^{-3} \) and \( Q \approx 60 \). For nematic LC devices of typically...
8-μm cell thickness the resulting sensitivity in terms of addressing voltage is ~5V, which is required for reflectivity modulation from $R = 0$ to 0.5. (see Refs. 6 and 17). Hence in these devices any sensitivity advantage that is gained from the SPR effect is small but could be increased in several ways. These include use of thinner LC cells in which less of the material modulation is wasted, use of materials such as smectic LC’s that have larger near-surface modulation, and use of lower-loss pseudoplasmom modes (which are described in Section 5).

In addition to reducing the sensitivity, the nature of the surface region in nematic LC devices also increases the response speed. This is also because of the stronger alignment forces at the cell surface and results in switching times of less than 2 ms in our devices, which is ~50 times faster than the bulk response time.17 This enhanced near-surface switching speed has been exploited previously in nematic LC SLM’s.22

C. Spatial Resolution Considerations

The advantageous resonant enhancement of the optical field in surface-plasmon SLM’s is due to the guided-wave nature of the plasmons. Guided waves are most commonly encountered in low-loss dielectric materials and have propagation lengths of the order of several millimeters or more. Because surface plasmons have some of their field in a metal they are relatively lossy and have propagation lengths of the order of 10 μm, which is quite suitable for SLM applications. Here we define propagation length as that over which the guided-wave amplitude falls by $1/e$, and for plasmons this is equal to $1/\Gamma_r$.

We have developed an analytic model for the propagation of plasmons on nonuniform surfaces.23 This is used to simulate the far-field diffraction pattern of the plasmon SLM and shows that the plasmon propagation length has a smearing effect on the image, such that the spatial resolution in the direction of plasmon propagation is limited to approximately the characteristic propagation length. More precisely we consider the case of a standard modulation transfer function (MTF) measurement in which the write beam consists of interference fringes. For the idealized case, in which the write-beam intensity is a sine-squared function of position and the SPR dip is shifted locally by a small amount $\Delta \beta \ll \Gamma$, ($\Delta \beta$ will be proportional to the write-beam intensity), we find that the 50% MTF point is exactly equal to $\Gamma_r$. Hence the spatial resolution of a SPR modulator can be estimated directly from the width of the SPR reflectivity curve.

For Ag/LC the theoretical value $\Gamma_r = 12$ line pairs (lp)/mm and the experimental values are ~17 lp/mm. For Ag/Si plasmons at a 1.3-μm wavelength the value that is inferred from reported SPR data11 is 13 lp/mm. In high-resolution optically addressed LC SLM’s the addressing field spreading within the layers of the device typically limits spatial resolution to less than 50 lp/mm (at 50% MTF).25 The spatial resolution limitations of surface plasmons, as given above, are therefore less than the maximum that is allowed by optical addressing. Among the disadvantages of surface-plasmon SLM’s we note that because of the high dispersion of metals the response is wavelength sensitive, although the SLM contrast can be optimized for operation at any chosen wavelength through the choice of metal thickness. Also, because plasmons are lossy, SPR is an intrinsically absorptive technique and this can be a disadvantage in applications that involve, for example, cascading of devices, for which low-loss modulation is desirable. In the present prism-coupled plasmon SLM’s the read beam enters the device at a relatively high angle of incidence. This complicates the output imaging optics, as outlined in Section 4, although the use of grating coupling can overcome this disadvantage by allowing a near-normal angle of incidence to be obtained.11

LC is the chosen active material for prototype surface-plasmon SLM’s because of the ease with which large-aperture devices can be fabricated. Some other material technology, either already demonstrated in a SPR modulator or yet to be considered, may prove to be more suitable for combining all the advantageous features of the SPR technique, as outlined above, in a single device. In the longer term the Si modulator11 is a possible candidate in this regard.

IV. Fabrication and Testing of LC-Based Optically Addressed Surface-Plasmon SLM’s

The present LC surface-plasmon SLM device is shown in Fig. 3. This takes the form of a typical LC light valve structure,26 with an amorphous Si photoconductor backplane providing the optical addressing capability. No light-blocking layer is present, and a plasmon-supporting Ag film forms the upper electrode. A nematic LC is used with homogeneous alignment in the direction parallel to the plane of the incident light. The top plate is a highly polished glass flat (type SF10) with a high refractive index, which, for optical testing, is attached to a coupling prism of the same material with a high-index-matching fluid (iodo-methane), as shown.

In fabrication, the Ag film is deposited first to the previously determined optimum thickness, which is 52 nm in our experiments. The photoconductive backplane consists of 3.4-μm-thick amorphous silicon, as described in Section 4.
Fig. 4. Plan view of the imaging system that is used for surface-plasmon SLM's. The plane of incidence of the read beam is parallel to that of the figure.

deposited on an indium tin oxide (ITO) -coated glass substrate. The LC alignment layer used consists of 25 nm of MgF$_2$, evaporated obliquely at 60° off normal incidence onto both the Ag and the Si. The cell is assembled with the alignment directions parallel, with Teflon strips as spacers, to give a cell thickness of 7.5 µm. Filling is by capillary action; nematic LC-type E47 (Merck) is used, and homogeneous alignment is obtained.

The electrical properties are modeled by using the equivalent circuit approach,
 in which each layer, including the spacers, is considered as a resistor and capacitor in parallel, with values determined experimentally. All voltages given are rms, and the circuit analysis shows that at a drive frequency of 20 kHz the voltage across the LC is switched by a ratio of 3:4 after writing the device with a saturating illumination. In order to improve on this switching contrast thinner cells are currently under development.

The system used for optical testing of the devices is shown in Fig. 4. In all measurements the TM-polarized, 633-nm-wavelength read beam is spatially filtered and collimated. For initial characterization of devices the SPR reflectivity curves are measured: (a) in the unbiased, unwritten state, (b) in the biased but unwritten state, and (c) in the biased and written state. Here written means under saturating illumination of the photoconductor with a 500-µW/cm² write beam, also of 633-nm wavelength. Typical SPR curves that are obtained are shown in Fig. 5.

From SPR assessment work the Ag optical constants are $\epsilon_m = -15 + j0.6$ and the MgF$_2$ alignment layer has $\epsilon = 1.9 + j0.001$ before cell filling. In the filled device the width of the SPR curve in the unbiased state indicates no changes in the alignment layer optical properties nor any additional loss that is due to the LC and, consequently, the larger-than-ideal SPR width is attributed to the losses that occur in the alignment layer. After biasing the device, however, as well as the expected shift in the SPR dip to higher angles of incidence, a decrease in depth and an increase in width occurs. This is attributed to electrically induced loss in the LC and, at the 3.5-V device voltage used, it is consistent with $\text{Im}(\epsilon) \approx 0.03$.

Figure 5 shows that the main plasmon reflectivity dip is shifted by only $\sim 1/10$ of its width after writing. This low sensitivity is due to the limited voltage contrast in the present device. For the 3.5-V bias voltage that is used this corresponds to a change in the LC voltage of approximately 1 V after writing, compared with the 6 V that are required for full modulation in electrically addressed devices. Although larger LC voltage switching is obtainable by using a higher bias, this further decreases the depth of the reflectivity dip because of increased losses in the LC. The overall light modulation contrast ratio of the devices consequently decreases for bias voltages larger than $\sim 4$ V. The response speed of the device is measured by using step-function changes in write-light level and the resultant read-beam rise and fall response times are both $> 3$ ms.

The two smaller, narrower reflectivity dips that occur near 68.2° and 69.8° in the biased state are due to coupling between the surface-plasmon mode and bulk guided modes within the biased LC cell. These modes, which have been studied previously, arise from the LC director profile in the biased cell; the director modulation is largest in the cell center, where the aligning forces are weakest, and this produces a graded refractive-index profile. The bulk TM modes of this graded-index waveguide are well confined within the LC and so have a much lower loss than the plasmons. Consequently coupling to these modes occurs over a narrower angular range, as shown in Fig. 5. The angular widths of these modes are larger than those observed in Ref. 6 and this is attributed to the larger LC losses and also the poorer cell thickness uniformity in our devices. The mode angular position, unlike that of the plasmon mode, is quite sensitive to cell thickness variations and this causes response nonuniformity over the measurement aperture. The net result is a loss of angular resolution in the SPR measurement by an amount that increases with the beam aperture. The cells reported here have a thickness uniformity of $\sim 0.5$ µm/cm and, for the 1-mm beam diameter used, this is calculated to produce a minimum angular resolution of 0.1° in Fig. 5.

Because of the lower loss of the bulk modes the sensitivity of our devices is increased in the region where the surface-plasmon–bulk-mode coupling oc-
curs and maximum switching contrast is obtained by operating at an angle \( \sim 69.8^\circ \), as indicated in Fig. 5. This maximum contrast position is used for the demonstration of image conversion with the device. As shown in Fig. 4, imaging of the SLM output is complicated by the fact that the beam that is modulated is incident on the device at an oblique angle. Because of the high refractive index of the prism the apparent object plane for coherent imaging of the output lies within the prism and is tilted with respect to both the plane of the device and the output beam direction. Consequently the diffraction plane and the output image plane are also not perpendicular to the optic axis, and so the video camera that is used to record the image must be tilted from the optic axis (Fig. 4). Using a demagnifying imaging arrangement can improve this situation, as the image plane is made more nearly perpendicular to the optic axis.

Another consequence of the oblique incident angle is that the SLM output images are compressed horizontally. For our devices this compression is \( \sim 50\% \), as shown in Fig. 6. The bright bands at the top and bottom of the output images are due to the Teflon spacers in the device, while the dark bands at either side mark the edges of the coupling prism, which are referenced as A and B in Fig. 4. In these images some increase in background intensity occurs toward the edges, and this is caused by the effect of cell thickness nonuniformity on the bulk modes. This is particularly evident in these large-aperture measurements at this angle of incidence while improved uniformity can be obtained, but with lower contrast, by operating at an angular position away from the bulk-mode resonance, by using the plasmon modulation alone.

The vertical fringes that are apparent in the output image of Fig. 6(a) are due to the interference of an additional reflection from the boundary between the prism and the top plate of the device. This effect can be eliminated, as shown in Fig. 6(b), by blocking the unwanted reflection at the Fourier plane, where it is spatially separated from the image beam. This separation arises because the top plate of the device has polished sides that are slightly nonparallel.

Figure 6(b) shows that the device has a lower spatial resolution in the horizontal direction than in the vertical direction; with decreasing size the sets of vertical bars disapper before the horizontal ones. This reduced horizontal resolution is due to both the optical image compression in this direction and the finite propagation lengths of the plasmon and bulk modes. To quantify these spatial resolution effects the MTF was measured by using the standard technique for optically addressed SLM's. This involves writing interference fringes on the device by using, in our system, a Michelson interferometer arrangement and by monitoring the first-order diffracted power from the SLM as the spatial frequency of the interference fringes is increased. In our experiments a 5-mm aperture was used for both the read and write beams, the latter having 500-\( \mu \)W/cm\(^2\) average power. Typical results are shown in Fig. 7 for the two cases of vertical resolution (written fringes parallel to the plasmon propagation direction) and horizontal resolution (fringes perpendicular to the plasmon propagation direction). The vertical resolution shown is 25 lp/mm at 50% MTF. This resolution is comparable to that of other optically addressed LC SLM's and is therefore probably limited by field spreading effects in the device, which has a total thickness of 11 \( \mu \)m (Fig. 3).

In horizontal MTF data the effects of the oblique angle of incidence have been corrected for. A lower spatial resolution of 13 lp/mm at the 50% point is measured in this case and this is less than that expected from the width of the SPR reflectivity dip of Fig. 5, which has \( \Gamma \approx 17 \) lp/mm. This reduced resolution is attributed to the contribution in the SPR response from the lower-resolution bulk guided modes. This result illustrates the sensitivity–spatial resolution trade-off of this type of device; for our relatively low-contrast addressing structure maximum contrast (sensitivity) is obtained by operating

Fig. 6. Examples of image conversion by a surface-plasmon SLM, showing input images (white light) and output images (coherent light at 633 nm).

Fig. 7. Measured MTF's: (a) vertical, (b) horizontal.
near the lower-loss bulk-mode angular position but this may result in reduced spatial resolution. Nevertheless the measured spatial resolutions are of a comparable order of magnitude to other SLM’s. In addition the results of Fig. 5 illustrate the large sensitivity improvement that could be obtained after increasing the switching voltage contrast in these devices. We are currently developing a thinner LC cell process for this purpose as well as considering new LC device designs in which the propagation loss of the plasmons can be controlled to optimize the sensitivity—spatial resolution performance for particular SLM applications. These designs involve the use of pseudo-plasmon modes that are described below.

V. Pseudoplasmon Mode Devices

To date our experimental work has concerned only LC structures in which the directors lie in the plane of incidence of the TM-polarized read beam so that the plasmon field remains purely TM. If other alignment configurations are employed the high anisotropy of the LC produces significant TM—TE polarization mixing effects and quite different modulation characteristics are obtained. To describe these effects we use the geometry described in Fig. 8. Here the tilt angle $\phi$ is the angle between the LC director $n$ and the layer plane, which is the $y$-$z$ plane, and the twist angle $\psi$ is the angle of rotation of the vertical plane containing $n$ about the $x$ axis with respect to the $x$-$z$ plane. For the homogeneous-alignment nematic LC devices described above the twist is always zero and no polarization mixing occurs. The initial tilt is approximately zero and is increased with increasing addressing voltage, which causes the TM surface-plasmon mode to move to higher $\beta$ (Fig. 5).

To assess the potential of surface-plasmon SLM’s it is important also to consider the newer, higher-speed, smectic LC materials, which are being used increasingly in display and SLM applications. In these materials the EO effects are obtained by modulation of the director twist, rather than tilt, and so, in a plasmon device, polarization mixing is always present and, in general, the reflected beam has elliptical polarization.

The behavior of surface electromagnetic waves on anisotropic substrates has been analyzed by using the fact that the field in the anisotropic material can be written as the superposition of two waves with different dispersion relations; these correspond to well-known ordinary and extraordinary rays for light propagation in the material. For evanescent waves, as for propagating rays, the ordinary wave-dispersion relation (ray refractive index) is constant while the extraordinary wave-dispersion relation varies with tilt and twist.

These phenomena are employed in the TIR switch, which is shown in Fig. 9(a) for comparison with the plasmon device shown in Fig. 9(b). In the TIR device the extraordinary wave is switched between evanescent (TIR) and propagating (transmitted) states while the ordinary ray is always reflected. To date the tilt modulation in surface-stabilized ferroelectric LC’s has been used in an optical configuration that is similar to that of the surface-plasmon device, as Fig. 9 shows. In both cases the ratio of splitting the incident field into ordinary and extraordinary waves in the LC depends on the incident polarization and LC alignment. The TIR device uses a TE rather than a TM read beam because this puts more of the incident energy into the extraordinary wave, giving larger transmitted intensity and lower insertion loss.

The switchable TIR phenomena can also be employed in surface-plasmon devices and, in this case, the situation in which the ordinary field is evanescent and the extraordinary field is propagating produces a leaky surface wave, which has been termed a pseudo-surface-plasmon mode, abbreviated to pseudoplasmon in this paper. The reflecting and transmitting states of the TIR device correspond to the surface and pseudoplasmon states, respectively, of the plasmon device. In the latter case the plasmon character is changed significantly after switching, and, since the pseudoplasmon is a much lossier wave than the surface plasmon (larger $\Gamma$), the width and depth of the SPR curve are both significantly altered. The metal film thickness can be chosen to optimize coupling to either the surface or the pseudo-plasmon mode, with the latter requiring a thinner metal layer to match the greater loss. The intensity of the propagating extraordinary ray, which would nor-
nally be small for a TM-polarized incident beam, can be significantly enhanced by the plasmon resonance effect. Furthermore, in director orientations at which the pseudo-plasmon mode occurs, the TM–TE polarization mixing is large and so the enhanced extraordinary ray has a significant TE component; so much so that such a plasmon device has been proposed as a switchable TM–TE polarization converter with a predicted efficiency of nearly 50%.

By determining the dispersion relations of these anisotropic plasmon modes the SPR curve resonance position ($\beta_r$) and width and depth ($\Gamma_r$) can be calculated as functions of $\psi$ and $\phi$. For the case of full tilt modulation only, from $\phi = 0^\circ$ to $\phi = 50^\circ$ at $\psi = 0^\circ$, we find that the SPR reflectivity dip angular position increases by $\sim 4$ times its width (FWHM) while there is virtually no change in this width. For the case of full twist modulation only, from $\psi = 0^\circ$ to $\psi = 90^\circ$ at $\phi = 0^\circ$, the SPR dip angular position decreases but only by $\sim 0.2$ times its width, while an increase in this width by a factor of $\sim 2$ now also occurs because of switching to the lossier pseudoplasmon regime for $\psi > 45^\circ$. These differences in response of the SPR curve to tilt and twist modulations arise from the structure of the plasmon optical field and they are explained below.

Since the plasmon electric field is associated with the surface charge on the metal it lies primarily in the direction that is perpendicular to the metal film, the $x$ direction in Fig. 8. The longitudinal field in the $z$ direction is smaller, with typically $|E_z|/|E_x| \approx 5$. This makes $\beta_r$ more sensitive to refractive-index changes in the perpendicular direction, which are only produced by tilt modulation, than to those that occur in the longitudinal direction, as produced by both tilt and twist. Significant changes in the plasmon loss parameter $\Gamma_r$ arise only if the character of the plasmons is changed. This occurs with increasing twist in the pseudoplasmon regime, since polarization mixing then causes an increasing proportion of the field to lie in the leaky extraordinary ray. Hence, for plasmons on a semi-infinite LC substrate, tilt modulation changes mainly the SPR curve position by changing $\beta_r$, while twist modulation changes mainly its width (and hence depth) by changing the modal character.

In the design of real devices that are based on these modes the analysis must incorporate the inevitable reflection of the extraordinary ray from the far side of the cell. In TIR devices this reflection is minimized by using a second, identical prism as the backplane [Fig. 9(a)] and by choosing the prism refractive indices to match those of the LC extraordinary ray in the transparent state. In SLM applications, however, the need for an addressing structure, which is usually semiconductor based and at the cell backplane, prohibits this approach. Use of the transmitted beam as the readout beam is then also inhibited, except for the case of planar optically addressed structures with infrared readout wavelengths. We have considered only those structures that are suitable for reflective mode readout with opaque semiconductor back-planes. The example chosen, which is shown in Fig. 9(b), represents the simplest LC SLM device that can be fabricated easily. The material optical constants used here are those of the device described in Section IV (Fig. 3), while the layer thicknesses are as detailed in Fig. 9(b). The high backplane reflectivity of this device could be reduced by using antireflection coating techniques but only over a limited angular range.

Backplane reflections set up a standing-wave pattern in the LC, which then behaves like a slab waveguide. As illustrated in Fig. 10, the pseudoplasmon resonance curve becomes separated into multiple resonance dips, each of which represents one slab waveguide order. Fig. 11 shows the field structure through the device both at a resonance [Fig. 11(a)] and between resonances [Fig. 11(b)]. This figure illustrates the mixed polarization of these guided pseudoplasmon modes; the TM field component is similar to that of the surface plasmon, and the TE component, which is produced mainly by the extraordinary ray, is similar to that of a slab waveguide mode; hence the guided pseudoplasmon modes have a mixed surface-wave–bulk-wave character. At each resonance it is mainly the TM plasmonlike field component that is enhanced [Fig. 11(a)] compared with the off-resonance state [Fig. 11(b)].

For each mode $R = 0$ can be obtained, with modulation as high as $R \approx 0.7$ after switching to a state in between resonances. This high-contrast, large dynamic range characteristic is attractive for SLM applications and is obtained because the large back-

![Fig. 10. Pseudoplasmon resonance reflectivity curves at 633 nm for $\psi = 0^\circ$, $\psi = 50^\circ$. The dashed curve is for a semi-infinite LC, and the solid curve is for a 2-μm-thick LC on a silicon backplane as detailed in Fig. 9(b). The TIR critical angle is 70.2° in this case.](image)

![Fig. 11. Amplitude envelopes of electric field intensity in the device of Fig. 9(b) for a unitary amplitude input beam: (a) at a resonance (68.6° in Fig. 10) and (b) between resonances (67.8°). The dotted curves show the TE field component and the solid curves show the total (TE plus TM) field. Note the distorted vertical scale.](image)
plane reflectivity is well matched to the high reflectivity of the Ag film at the top of the cell, which produces a symmetric waveguide. Although guided modes could also be produced in a reflective readout TIR device with a semiconductor backplane, the waveguide would then be highly asymmetric because of low reflectivity at the top of the cell [Fig. 9(a)] and consequently deep reflectivity minima could not be obtained easily in that case.

Unlike the surface plasmon the guided pseudoplasmon modes are sensitive to both twist and tilt modulation and this characteristic can be explained by Fig. 11. At resonance the TM part of the field, which is sensitive to tilt modulation, has enhancement and depth that are similar to that of the surface plasmon, while the TE part, which is sensitive to twist, is now also enhanced, to a lesser degree but over a larger depth of LC. This leads to similarly high sensitivity for the two types of modulation, and so the reflective mode guided pseudoplasmon device can be used with a wide range of LC materials.

As well as their high-contrast characteristics and material versatility, a third attractive feature of guided pseudoplasmon modes for use in SLM's is their controllable loss. As can be seen from the width of the resonances in Fig. 10 this loss is several times less than that of the surface plasmon. This is because a larger proportion of the field now lies outside the metal in the LC, where it is enhanced by multiple reflections. The loss of the pseudoplasmon modes (and their angular separation) can be increased by decreasing the cell thickness, as this forces a higher proportion of the field to lie in the lossy metal and semiconductor regions. The loss of each individual mode can also be controlled by varying its angular position, and this is illustrated in Fig. 12, where in (a) the mode angular position and in (b) the total optimized coupling loss $\Gamma_1 = 2\Gamma'_1$ are plotted versus increasing twist angle. The enhancement of the TM (surface-plasmonlike) part of the field and, consequently, the proportion of field in the metal are greatest at the original resonance position (i.e., such as in the case of a semi-infinite LC, which is labeled nonguided pseudoplasmon in Fig. 12), and so the loss of each mode increases with its proximity to this position. The spatial resolution that is obtainable with these modes is therefore controllable through the choice of the LC twist orientation.

In Fig. 12(b) the mode loss is calculated by the modal field distribution at resonance from the power absorbed in the metal and semiconductor layers. It is, however, not valid to infer spatial resolution from these field data when the mode lies close to the critical angle for TIR of the extraordinary ray. This is because the direction of ray propagation in the LC is then nearly parallel to the cell surface. The numerical modal field analysis that is used here assumes an infinite length of LC surface and so it is valid only to infer spatial resolution from the data when the longitudinal distance (in the $z$ direction) over which the $e$ ray traverses the cell is much less than the pixel size under consideration. For the example device with 2-µm LC thickness this validity condition is the fact that the mode lies more than $\sim 1^\circ$ below the critical angle and the corresponding resolution-invalid region is indicated in Fig. 12(a).

Because pseudoplasmons have a lower but readily controllable loss compared with surface plasmons, they can be used to optimize the sensitivity–resolution trade-off in various SLM applications if we choose the cell thickness and twist operating point accordingly. The cell thickness must also be small enough to make the intermode separation significantly larger than the mode width so that large reflectivity modulations are obtainable. For our example device and a typical SLM spatial resolution requirement of $\sim 10$ lp/mm a suitable operating point is that labeled A in Fig. 12. This is the third-order pseudoplasmon mode at a twist orientation of 52.5° and with the $R = 0$ dark state obtained at an angle of incidence near 68°. A twist modulation to 48.5° then produces reflectivity modulation by moving the device to a state between resonances, which is marked B in Fig. 12(a), and the full SPR reflectivity curves corresponding to these conditions are shown in Fig. 13. This high sensitivity of 5° director modulation that is required for a reflectivity modulation from $R = 0$ to 0.7 probably represents the maximum that is attainable

![Fig. 12](image-url)
with guided modes within the chosen SLM spatial resolution constraint of 10 lp/mm. Such enhanced sensitivity would be useful, for example, with the new electroclinic LC materials, which often exhibit a high response speed at low twist modulation, or with existing materials such as nematic LC's, in which increased response speed or sensitivity could also be obtained.

In utilizing guided pseudoplasmons the single interface advantages of surface plasmons are sacrificed to some extent, since the response is susceptible to cell thickness nonuniformities. For the above example a cell thickness variation of 0.1 μm in the device would produce a reflectivity variation of 5% at worst. To retain the uniformity advantages of the surface-plasmon mode we might consider devices that switch between the surface-plasmon and pseudoplasmon states. For example a uniform dark state could be obtained at a surface-plasmon resonance while the high reflectivity state, in which response nonuniformity is less critical, could be obtained upon an increase in the tilt or twist angle that switches the device into the pseudo-plasmon regimen.

The use of pseudoplasmon modes also means that the light blocking and planarization layers of conventional LC SLM's may have to be reintroduced since otherwise significant writing of the backplane can occur through mode absorption in the semiconductor. Alternatively this read-beam leakage could be used to produce nonlinear SLM responses, as in previous leaky-mirror LC light valve devices. In the case of pseudoplasmon modes the amount of read-beam leakage increases with field enhancement and is maximum when the device is at resonance and is minimum between resonances. The addressing signal feedback that is produced by this leakage mechanism could therefore be used to drive the device from an off-mode state with low leakage and high reflectivity toward an in-mode state that has maximum leakage and low reflectivity with a high degree of nonlinearity. As in the leaky-mirror light valve functions such as optical thresholding are envisaged. In both types of device the nonlinearity arises from strong polarization mixing effects in the LC while the pseudoplasmon device would have a simpler, all-planar structure. In addition the guided-mode nature of the plasmon device could lead to new functional capabilities. For example, when operating at resonance, all portions of the device are in a maximum leakage state. If this leakage is significant any local variations in material properties or LC cell thickness are then taken up by a compensating shift in local addressing voltage such that all portions of the device remain at resonance and hence with uniformly low reflectivity. Such a self-leveling capability could also be useful in other applications in which response uniformity is of prime concern, for example, in large-aperture shutters.

In this initial discussion we have assumed the LC director orientation to be uniform throughout the cell. In real devices complicated director profiles are present and must be included in the analysis by using a multilayer description of the cell. Nematic LC's have been studied in some detail in this respect with SPR and related guided waves, and, more recently, the same methods have been applied to smectic LC's. Pseudo-plasmon SLM device development work should both draw upon and contribute to this area of LC material characterization.

VI. Concluding Remarks

A nematic LC-based prototype surface-plasmon SLM has been demonstrated. The spatial resolution in the direction parallel to the plane of incidence is found to be limited by bulk guided-mode effects but is nevertheless comparable with that of other LC SLM devices. This device is still in its early stages of development and an improvement in sensitivity and contrast has been obtained recently by the implementation of a thinner LC cell process. The next stages of device development involve assessment of the expected plasmon-related response uniformity advantage and the development of smectic LC devices that are based on pseudoplasmon modes.

The design of these smectic LC SPR devices has been described in particular with respect to the use of guided pseudoplasmon modes in reflective readout devices. It has been shown that these modes are well suited to the production of high-contrast reflectivity modulation in simple LC–semiconductor structures and that they have other attractive features for use in SLM's. These include controllable sensitivity–resolution characteristics and interesting nonlinear capabilities.

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References


Fig. 13. Example modulator reflectivity curves calculated at φ = 0°, ψ = 52.5° (solid curve), and ψ = 48.5° (dashed curve) for the device of Fig. 9(b). High-contrast modulation occurs near θ = 68° from the third-order pseudoplasmon mode resonance position, which is marked A as in Fig. 12, to midway between modes, which is marked B as in Fig. 12.


