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Polymeric Electrooptic Light Modulator Based on Grating-Coupled Surface Plasmon Resonance

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Introduction

Electrooptic (EO) modulators have attracted considerable attention due to their potential applications in ultrafast optical information processing and optical communications.[1,2] Polymeric materials offer significant advantages in the fabrication of EO modulators.[1] Because of their low dielectric constants, fast electronic response, high EO activity, and high processability of polymer materials, EO modulators possessing ultrahigh speed, wide-bandwidth, low half-wave voltage (V_π) and low cost can be prepared. Currently the common configurations of polymeric light modulators are Mach-Zender interferometer, birefringent modulator and the directional coupler.[2,3] The polymeric modulators with the modulation speed of 110 GHz and low modulation voltage of 0.8 V have been demonstrated.

Surface plasmon refers to a propagating electron-density oscillation at a metal-dielectric interface caused by the illumination of the metal surface under appropriate conditions.[4-6] When a monochromatic, *p*-polarized beam of light is incident on a metal-dielectric interface at an appropriate angle, energy from the light can be coupled into electrons in the metal. The incident angle for which the maximal coupling of light energy into the surface plasmons occurs is manifested by a sharp decrease in the reflected intensity of the incident beam. Consequently, the surface plasmon resonance phenomenon (SPR) can be exploited to modulate the reflection of light via control of the factors that affect the resonance conditions such as the refractive index of dielectric medium and the angle of incidence or wavelength of the incident light.[5,6]

However, it should be noted that the SPR phenomenon cannot be observed by illuminating on a planar metal surface, since the propagation constant of the surface plasmon is always greater than that of the incident light.[4] To achieve surface plasmon coupling resonance, the propagation constant of the incident light along the interface should be equal to that of the surface plasmon. This problem is typically circumvented by using a prism-coupling method, so-called Kretschmann configuration, as shown in Figure 1(a). In this method, a metal film is brought into optical contact with a high-index glass prism. The illumination of the metal layer is performed through the prism at an angle greater than the critical angle for total internal reflection. The prism with the high refractive index increases the propagation constant of light. Under these conditions, the surface plasmon can be excited. An alternative to the Kretschmann configuration is the grating coupling method, as shown in Figure 1(b). This is implemented by coating a diffraction grating with a thin metal film. The diffraction grating is a periodically modulated interface between two media. A light wave incident on a grating is diffracted into

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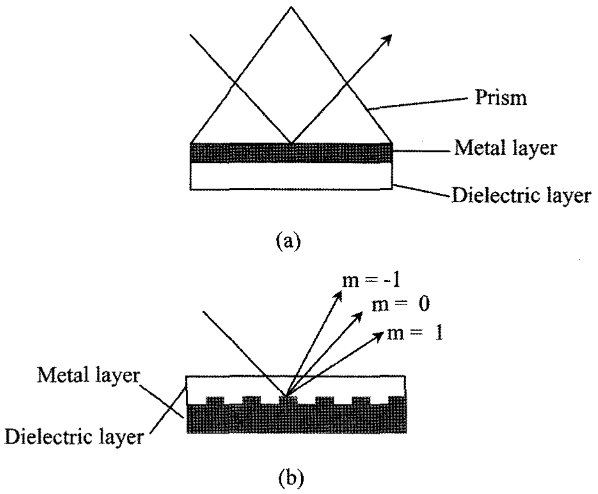

Figure 1. Schematic optical configurations on surface plasmon resonance. (a) Prism-based SPR system, which is called as Kretschmann configuration and (b) Grating-coupled SPR system, where the *m* is the order of diffracted light.

various orders. With the proper selection of the angle of incidence, the wavelength of the incident beam and the grating periodicity, a diffracted beam can be made to have the propagation constant along the interface that matches that of surface plasmon.

Until now, most SPR systems have been based on Kretschmann configuration. The light modulators reported during the last decade also used the prism coupled SPR method.[5-7] However, for optical applications, the grating-coupled SPR method provides significant advantages over the prism-coupled method in terms of the size, the cost, the configuration flexibility, and easy integration with the circuit boards, the modules, the integrated circuits. Despite these advantages, its application has been limited because of the greater complexity of fabrication required to make the gratings. However, this problem can now be circumvented by the recent technological advances in plastic optical grating fabrication methods. Plastic optical gratings can now be mass-produced at very low cost using the same technology that is used to produce DVDs (digital video disks) or CDs and could be formed in spin cast layers. Recently, Fernandez, one of the authors of this paper, developed a microarray-based grating-coupled SPR biosensor system for proteomics applications.[8]

Consequently, in this work, we attempt to apply the grating-coupled SPR phenomenon to the fabrication of an EO light modulator. The modulation of light based on grating-coupled SPR is demonstrated using the side-chain nonlinear optical polymer.

Experimental

Materials. The side-chain nonlinear optical polymer, poly(methyl methacrylate) with pendant *N*-methylamino-4'-nitroazobenzene chromophore, was synthesized as described previously[9] and its chemical structure is shown in Figure 2. Its absorption maximum determined by UV-Vis spectrometer (Perkin-Elmer Lambda 900 UV/Vis/NIR spectrometer) is 500 nm. The glass transition temperature of polymer determined by Differential Scanning Calorimetry (Perkin-Elmer DSC 7) at the heating rate of 10 °C/min is 93 °C.

Device Preparation. The configuration of the EO device is illustrated in Figure 3. The gold film of 500 Å in thickness was deposited on polycarbonate grating substrate having a dimension of (1 inch square), supplied by HTS Biosystems. The surface of polycarbonate substrate has very fine gratings, with the grating period of 0.8 μm and the grove depth of ca. 60 nm. After filtering polymer solution (8% wt in cyclohexanone) through 0.2 μm filter, a thin polymer film with the thickness of 0.1 μm was prepared by spin-coating and dried at 90°C in a vacuum oven for 24 hrs.

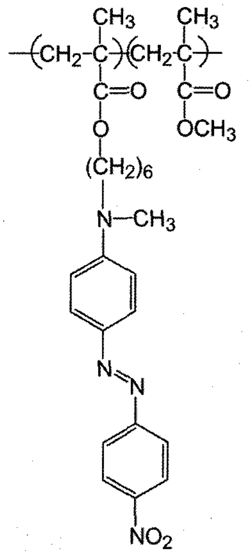

Figure 2. Chemical structure of side-chain nonlinear optical polymer used in this work.

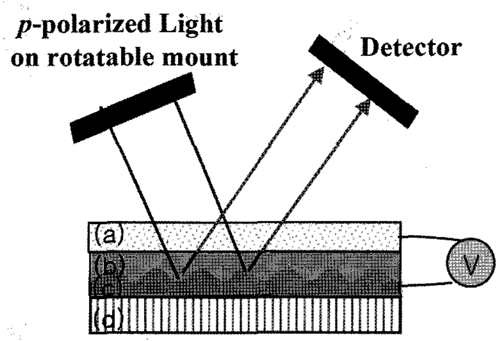

Figure 3. Schematic optical configuration used for SPR measurement. (a) ITO transparent electrode, (b) electro-optic polymer, (c) gold electrode, and (d) polycarbonate grating.

Transparent ITO electrode was deposited on polymer film by the low temperature DC-sputtering method by Thinfilms Inc, New Jersey. The temperature of the substrate was kept below 100 °C and ITO was deposited on the polymer film through a mask. The resistance of the ITO electrode was 35 Ω/cm^2.

The electrooptic polymer was poled by the application of an electric field of 50 V/μm at 90 °C for 5 min and then slowly cooled to room temperature with the poling-field on. The poling process removes the centrosymmetric arrangement of chromophore to translate the molecular optically nonlinear property into macroscopic electrooptic property.

Measurement of Surface Plasmon Resonance (SPR). The schematic optical configuration used for measuring the SPR condition is given in Figure 3. This system provides sequential illumination on the device at a series of incident angles and imaging detection of the reflected intensity at each angle. Mono-chromatic, *p*-polarized light was provided by a 16 mW 870 nm LED (Hewlet Packard HSDL-4400) through collimating optics, a polarizer and a narrow band-pass filter. The polarizer selects *p*-polarization required for coupling into surface plasmons, since only *p*-polarized light will excite the surface plasmons at the metal-dielectric interface. The band-pass filter is necessary to achieve narrow resonance curves (and thus high sensitivity) because the spectral width of the LED is 37 nm. A high degree of collimation is also required to obtain narrow resonance curves. The illumination system (LED plus optics) was rotated about a horizontal axis perpendicular to the plane of incidence and collinear with the mid-line of the device. Rotation was effected with a stepping motor drive in user-selectable angular increments (minimum of 5 millidegrees). The camera was a TE-cooled scientific grade CCD camera with 1317 × 1035 (6.8×6.8 μm^2) pixels and 12-bit digitization (Photometrics Quantix). The quantum efficiency at 870 nm is ~30% and the frame transfer rate is 2.5 frames/sec. The detection optics has a magnification of approximately 0.54. For a determination of SPR condition, the intensity of reflected light was monitored by CCD camera as the light source was rotated through an angular range of 5.2 °.

Results and Discussion

In order to determine the surface plasmon resonance condition, the intensity of reflected light was measured as a function of the incident angle. As shown in Figure 4, the SPR resonance condition is manifested by a large decrease of the reflected intensity of the incident beam, near the angle of 38.65 ° where the reflectance intensity shows a minimum. It is denoted as a SPR angle (θ_{SPR}) and corresponds to the condition where the optical coupling of the incident beam and surface plasmon is maximized. No resonance curve is observed with *s*-polarization.

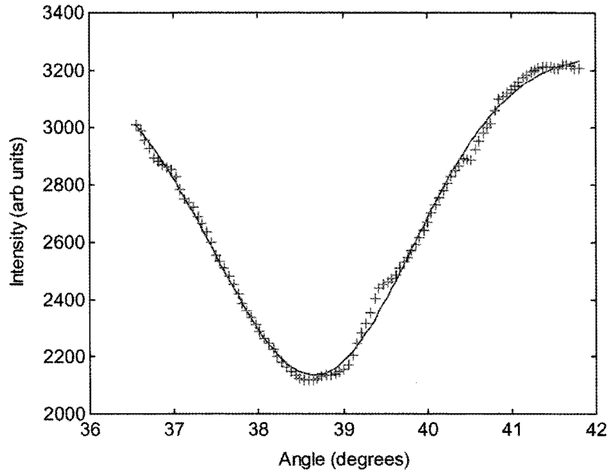

Figure 4. Reflected intensity versus the angle of incident beam of EO modulator at 870 nm.

At the resonant angle of incidence, the reflectance minimum is associated with coupling from a diffracted beam into a surface plasmon wave. That is, the surface plasmons cannot be directly excited by the illumination of a *planar* metal surface due to the momentum mis-match between the surface plasmon and the incident light.[4] However, when the light is incident on a diffraction grating, it is diffracted into various orders and at the higher diffracted order, the momentum component along the grating plane can be matched with that of the surface plasmon. By choosing the proper angle of incident beam, the light energy is transferred to surface plasmon which lead to a decrease in reflected light, as observed in Figure 4.

In order to demonstrate the capability for light modulation with our device, the variation of the SPR condition with the application of an electric field was determined. Figure 5 shows the periodic variation of the θ_{SPR} when 5 V was applied to the device and turned off. It clearly demonstrates the control of θ_{SPR} by the change of applied field.

The SPR condition is very sensitive to the variation of the optical properties of the dielectric medium adjacent to the metal layer supporting the surface plasmon wave. That means that it strongly depends on the variation of refractive index of the EO polymer. When the EO polymer film is subjected to an electric field (E), the refractive index change (Δn) can be described in eq. (1):

$$\Delta n = \frac{n_0^3 r E}{2} \tag{1}$$

where n_0 is the index of refraction of the polymer in the absence of an applied field and r is the electrooptic coefficient.[10] Thus the value of θ_{SPR} for a given device can be modulated by the variation of the applied field. Figure 5 demonstrates the feasibility of the current device as a poten-

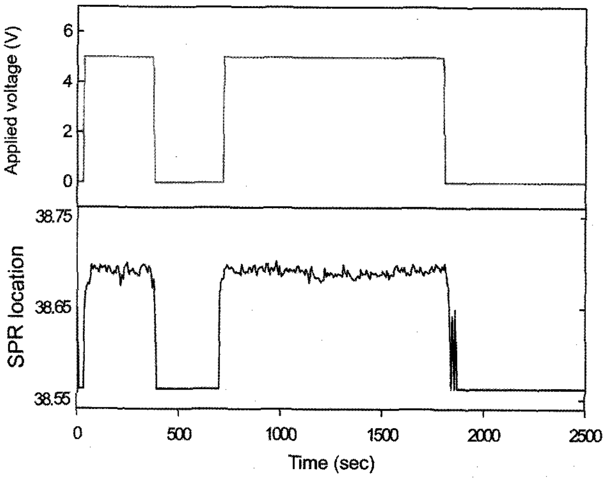

Figure 5. The modulation of light by the application of voltage (5 V).

tial EO light modulator.

The current polymer possesses an index of refraction of approximately 1.7 and an EO coefficient of 12 pm/V at 50 V/μm, which was measured using a simple reflection technique suggested by Teng and Man.[10,11] Assuming bulk effects for the interaction of the evanescent wave, and using eq. (1), a change in the index of refraction of 1.5×10^{-3} is predicted. Previous work with the SPR grating as a sensor with a protein plus water coating shows a change in angle of 100 milli-degrees for such a change in the index of refraction.[8] Thus, the measured change of 100 milli-degrees with our model is considered in agreement with predicted results.

Conclusions

In summary, in this work, we demonstrated the application of the grating-coupled SPR for the fabrication of an EO light modulator. SPR-based EO modulators reported to date have mostly used the Kretchmann configuration. To the best of authors' knowledge, this work reports the first fabrication and demonstration of a grating-coupled EO modulator. By switching on and off of the applied voltage of 5 V, the subsequent variation of SPR was observed clearly. It should be mentioned that currently our study was limited to show the feasibility of our concept. For practical applications, further optimization of SPR signal will be required, which is a subject of our ongoing research.

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