# Optical modulation processes in thin films based on thermal effects of surface plasmons

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Experimental results are presented for light-on-light modulation at low rates using coupling to nonradiative surface plasmons and their associated thermal effects in a thin gold foil. It is first shown that several modulated Gaussian beams simultaneously exciting surface plasmons in the same region of a thin gold film, will result in a coupling that is revealed in the reflected beams. The observed effects result in the reflected beams undergoing changes in both spatial distribution and intensity levels. A brief study is then presented of the coupling between surface plasmons and an electrical current in the excitation region to further support the role of the surface plasmon induced thermal processes in the gold foil.
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Modulation of light at low modulation rates is useful for analog signals extending from visual perception rates up through the audio range. A simple method of changing the wavelength of the carrier is described here in which no electronics, phase change effects, or nonlinear crystal effects are necessary. Surface plasmons[1] (SPs) and their associated electromagnetic waves, result from collective oscillations of the electrons at a metal-dielectric interface, and are of a growing interest in areas such as surface characterization, field enhancement, and sensing.[2] They are also attractive candidates within the framework of developing integrated photonic components, especially those motivated by the demands in telecommunication. Recently, coupling mechanisms based on SPs, were reported that demonstrated light by light,[3] and optoelectronic[4] modulations. These processes seem to be promising for "optical" modulation, and have the potential for leading to innovative applications and improving integrated components such as modulators,[5–8] filters,[9] or switches.[10] In this article, we report thermo-optical processes, where SPs play a necessary role, to create optical modulation using simple devices. We first present various aspects of the behavior of surface plasmon assisted coupling (SPAC), including the variation in the polarization state. We then study a SP-current coupling to explain the thermal contribution encountered in SPAC.

A scheme of our setup, based on the Kretschmann configuration,[11] is given in Fig. 1. The configuration for SPAC is described in Fig. 1 (top left), and involves a thin gold film of a thickness optimized for the excitation of the SP by the infrared (IR) pump laser beam ($\lambda_1 = 1550$ nm), incident at the peak resonance angle 43.6° (Fig. 1, bottom left).

A second beam, in our case a Helium-Cadmium (HeCd) line of $\lambda_2 = 442$ nm, is brought in the IR SP region, and is used as a probe beam. Under these film characteristics, the probe beam possesses a broad absorption peaked at around 58°, as shown in Fig. 1 (bottom right), allowing the excitation of the second SP. Every used Gaussian beam is, preliminary, linearly polarized, using a combined linear polarizer and polarization rotator. The reflected beams are then profiled to study the plasmons coupling.

The mutual effect of SPAC is illustrated in Figs. 2(a)–2(d) by profiling the reflected probe (with an output power of 20 mW) and pump (with an output power of 165 mW) beams, without and with coupling. Variations of the

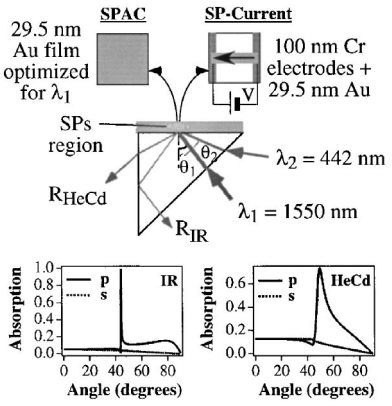


FIG. 1. Experimental schemes for SPAC (top left) and SP-current coupling (top right). The Kretschmann configuration is utilized to excite SP using a 29.5 nm gold film, optimized for the wavelength of the pump laser beam $\lambda_1 = 1550$ nm. In top left a linearly polarized HeCd line ($\lambda_2 = 442$ nm) is used as a probe beam. The absorption curve for the IR is displayed in bottom left. At the resonance angle $\theta_1 = 43.6°$, the absorption is almost total for *p* polarization and is below 3% for the *s* polarization. In the case of the HeCd beam incident at $\theta_2 = 58°$ (bottom right), 46 and 8% absorptions, for *p* and *s* polarization, respectively, are observed.

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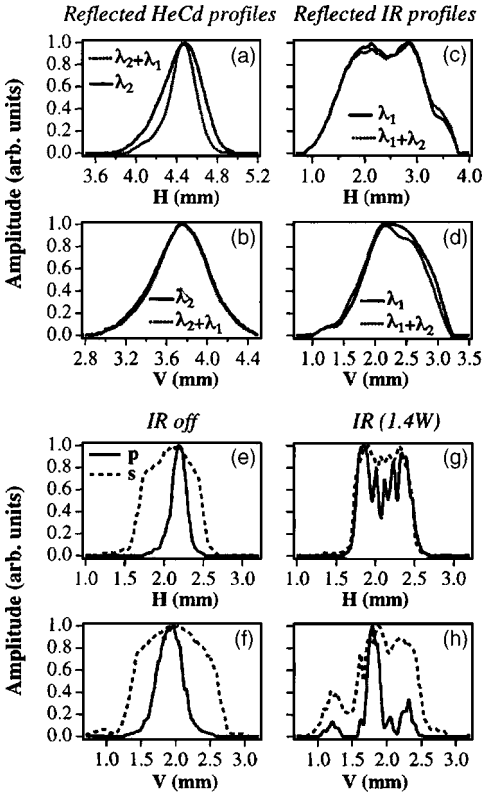


FIG. 2. Reflected beams profiles showing the mutual effect of SPAC (a)–(d) and the effect of the probe beam polarization state (e)–(h). (a) and (b) display the horizontal and vertical HeCd reflected beam profiles, respectively, without (solid curves) and with (dotted curves) IR. (c) and (d) represent the IR reflected beam profiles without (solid curves) and with (dotted curves) HeCd influence. In this case, the used incident power levels are 20 mW for the HeCd and 165 mW for the IR, and the two beams are *p* polarized. (e) and (f) show the HeCd reflected beam profiles for *p* (solid curves) and *s* (dashed curves) polarization with no IR, while (g) and (h) display the corresponding curves with IR (with an output power equals to 1.4 W). The abscissas (*H* and *V*) give the beam dimensions, while the ordinate represent the variations of the profiles intensity in the two directions.

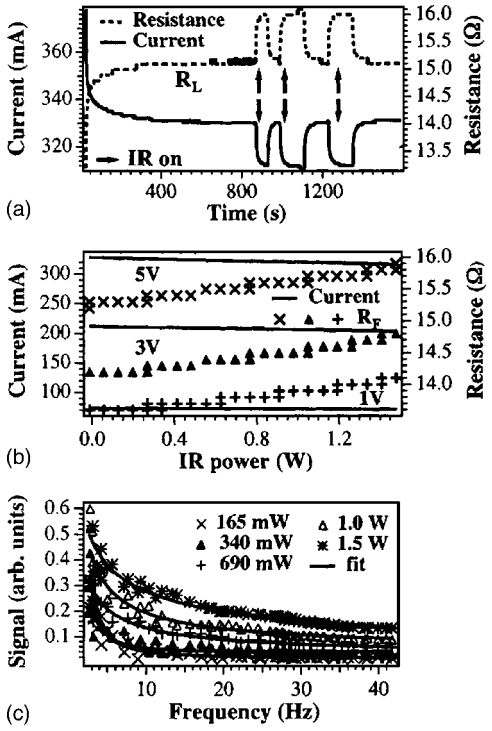


FIG. 3. SP excitation in thin gold films in the presence of resistive heating with the aim of providing further modulation processes related to SPAC. (a) shows the variations of the resistance of the foil (nominal $R_N = 13.2\ \Omega$) as a function of time, while imposing a constant 5 V potential across it. After a fast increase of the resistance due to the applied potential, the resistance reaches a stationary value ($R_L = 15.1\ \Omega$ for this particular potential). At 850 s, the IR laser is turned on at full power (1.5 W) for one minute, and then, for two minutes at 950 and 1250 s. The thermal contribution, induced by the laser, shows a new increase in the resistance, which reaches a new limit value of 16.0 Ω, and returns to its original value as the laser is turned off. In (b), we monitor the resistance of the same foil at three different potentials, while the IR laser power is increased in regular steps. For each step, the resistance increases to reach a stable value. In (c), the signal for a 3 V potential is plotted as a function of the IR beam modulation frequency *f* at different power levels.

beams shapes are observed in both cases. The HeCd beam undergoes a focusing effect, resulting in a 20% width reduction at the full width at half maximum (FWHM). For the IR beam, smaller local changes are observed, just as a 1% size reduction at the FWHM. In order to better assess the intensity variations, each profile has been integrated as follows: $A_h = \int_H \Phi_i dh$, horizontally, and $A_v = \int_V \Phi_i dv$, vertically where $\Phi_i$ is describing the profile, and $H = [h_1, h_2]$ and $V = [v_1, v_2]$ are the intervals of integration. By doing so, we show the capability of this coupling for intensity modulation. In Figs. 2(e)–2(h), we discuss the influence of the polarization state of the probe beam. We notice that the shift from *p* to *s* of the IR pump beam polarization conduces to a complete vanishment of the effect. This is explained by the simulation of the IR absorption for both polarizations (Fig. 1, bottom left); almost 100% absorption is observed at the resonance angle for the *p* polarization, whereas only a 3% is predicted for *s*. In Figs. 2(e) and 2(f), we profile the *p* and *s* HeCd reflected beams with no other beams present. The *s*-polarized beam profile is wider than the *p* polarized, likewise the intensity level is larger, as expected by the SP properties. Figures 2(g) and 2(h) display the measurements, when influenced by the IR SP (at full power 1.5 W). We clearly observe variations in the beam shape, larger for *p* than for *s* polarization. We expect larger changes for *p* polarization, due to a higher absorption, according to Fig. 1 (bottom right), than the 8% absorption for *s* polarization, at the resonance angle.

In the last part of this article, we investigate the thermal contribution occurring during SPAC. We, thus "replace" one of the beams (the probe in this case) by a current flowing across the film. The experimental scheme is described in Fig. 1 (top right). Chromium electrodes are evaporated before the 29.5 nm gold film, to establish connections to an external power. In order to limit the effect of the current to the laser illuminated region, the gold film is made narrow of the dimensions of the beam. The foil resistance (nominal $R_N = 13.2\ \Omega$) and the current, are then monitored while changing either heat sources (IR or current). Figure 3(a) illustrates the resistance evolution, when a 5 V potential difference is applied to the film. After the film reaches the steady limiting value $R_L = 15.1\ \Omega$ at this potential, we alternately submit the foil to the IR SP; each time, an increase in the resistance is observed, which reaches a new limit of 16.0 Ω. The resistance returns to $R_L$ as the IR is turned off and to $R_N$ as we interrupt the potential. As expected, the opposite behavior is observed for the current. Figure 3(b) displays the same measurement as Fig. 3(a), for different potentials. In each case, a stationary state is reached before involving the IR excitation. The IR contribution increases the foil resistance (below 1 Ω) fairly identical for each used potential. Finally, in Fig. 3(c),

we turn our interest to the effect of time exposure of the foil to the IR laser beam, by mechanically modulating the IR beam in a frequency range $f$ up to 40 Hz. This measurement is carried out for IR power levels from 165 mW to 1.5 W, when the potential across the film is maintained at 3 V. Beside an overall increase of the signal as a function of the power, a drop in the signal is observed as the frequency increases. A possible $1/f$ dependence is fitted to each curve, which could prove, in analogy with Joule's law, the time dependence of this coupling for low frequency range. As a first approach, to better optimize our experimental observations presented in Fig. 3, we may take the electric field and the current density in the gold foil to be connected by the simple temperature dependent resistivity $r(T)=r(T_r)[1+\alpha(T-T_r)]$, where $\alpha$ is the thermal resistance coefficient. Then, solving for the scalar electric potential of the resistive heated foil $-\nabla.[\sigma(T)\nabla V]=0$, where $T$ evolves according to the heat diffusion equation $\rho\, c_p \partial T/\partial t - \nabla.(k\nabla T)=\cos(2\pi ft).\sigma(T)|\nabla V|^2+q$, where $\rho$, $c_p$, and $k$ are the density, heat capacity, and thermal conductivity of gold respectively, $f$ is the modulation frequency, and $q$ contains the effects of the heat transfer by radiation and convection. These considerations are currently in progress.

In conclusion, we demonstrate that SPAC can be used as a means for modulation with a reciprocal behavior, especially if using the same laser power levels, and where polarization can be a parameter to realize modulation. By studying the polarization states, we also believe that this device could be adapted in the aim of creating an optical switch by only rotating the pump beam polarization from $p$ to $s$ or by using a probe with a "$s$ absorption" close to zero. We then established a relation between the thermal contribution and the IR excitation, by experimentally monitoring the resistance of the film and the current. We show an increase of the resistance, as a function of IR power, and thus of temperature.

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