Excitation of a surface plasmon with an elastomeric grating

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We report on a new method to excite surface plasmon polaritons on a thin metal slab surface using an elastomeric grating which is fabricated by replica molding technique. The grating is placed on the metal surface which creates a periodic perturbation on the surface matching the momentum of the incident light to that of the surface plasmon. The conformal contact between the metal surface and the elastomeric grating changes the dielectric medium periodically and allows the observation of an effective surface plasmon polariton at the metal-air and metal-polymer interfaces of the grating. To clarify the nature of the observed plasmon, comparison of the elastomeric grating with elastomeric slabs was performed with the attenuated total reflection method. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2222344]

Surface plasmon polaritons (SPPs) are electromagnetic waves localized on the surface of a metal and dielectric interface and coupled to the collective oscillations of free charges. Due to highly confined features and sensitivity to changes in the surface properties, SPP's have found diverse area of applications ranging from optics[1–3] to biological sciences.[4]

SPP's are excited and propagate on the surface of the conductor as a result of the interaction between electromagnetic field and metal covered by a dielectric medium. Solving Maxwell's equations with appropriate boundary conditions yields the well known dispersion relation[5] for k_{SPP} as

$$k_{\mathrm{SPP}} = k_0 \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}} = n_{\mathrm{SPP}} k_0, \tag{1}$$

where k_{SPP}, k_0, ε_d, ε_m, and n_{SPP} are wave numbers of the SPP and the propagating light, dielectric function of the dielectric medium and the metal film, and effective index of the SPP, respectively.

From the dispersion relation given above, it is clear that the SPP wave number k_{SPP}, is greater than that of the free space photon when $\varepsilon_d \geqslant 1$ and $\varepsilon_m < -\varepsilon_d$. However, resonant coupling can only occur when the momentum of the incident light matches to the momentum of the SPP. There are two common methods to overcome this momentum mismatch. In the first method, surface plasmon resonance (SPR) can be achieved under conditions of attenuated total reflection (ATR). The idea for the use of ATR goes back to the work of Otto[6] and Kretschmann.[7] In this configuration, a prism having high refractive index enhances the momentum of the incident light when the sample is illuminated from the prism side. By scanning the angle of incidence, the resonant excitation can be achieved. The second method utilizes a grating fabricated on the surface of the metal that acts as a coupler. Due to the periodic corrugation on the metal surface, the momentum of the light is increased. This property of the metal grating allows to excite the SPP from both sides of the grating.[5]

In this letter, we report on a new approach to couple incident light to a plasmon mode in a thin metal layer. In our approach, we use a polydimethylsiloxane (PDMS) (Sylgard 184) elastomeric grating stamp to excite a surface plasmon on flat metal surfaces without the use of a prism and without creating any permanent corrugation on the surface of the metal. Recently, we used the same technique to couple free space light to the guided modes of optical waveguides.[8,9] The elastomeric grating stamp is fabricated by the replica molding technique. For this purpose, we employ a commercially available ruled grating with groove density of 1200 grooves/mm. Then liquid PDMS is poured onto the master grating and a polished wafer is placed on the top surface with rigid separators in order to obtain planar and smooth surfaces. Finally, the elastomer is cured at 70 °C for 3 h in air and the PDMS stamp [n_{PDMS}=1.41 (Ref. 10)] is peeled off from the master grating. The thickness of the PDMS grating stamp is approximately 5 mm. The sample to be studied was fabricated as follows; a 5 nm thick Ni followed by 45 nm thick Au film is deposited onto a glass cover slide by thermal evaporation. The elastomeric grating stamp is placed on the gold surface as shown in the schematic description of the structure in Fig. 1. Coupling occurs when the Bragg equation is satisfied,

$$k_{\mathrm{SPP}} = k_0 \sin(\theta) + m\frac{2\pi}{\Lambda}, \tag{2}$$

where k_0 is the wave vector of the incoming light with incident angle θ, k_{SPP} is the wave vector of the SPP, θ is the angle of incidence, Λ is the period of the grating structure, m is an integer that defines the order of scattering process, and $k_0 \sin(\theta)$ is the horizontal component of the wave vector. By

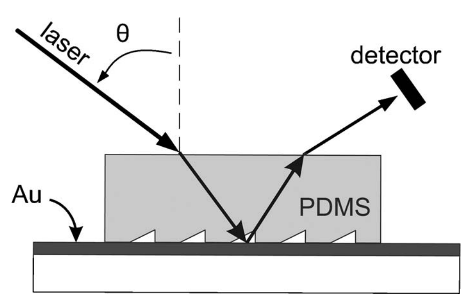

FIG. 1. Schematic of the experimental arrangement for excitation of SPP. Reflected power decreases when the resonance condition is met.

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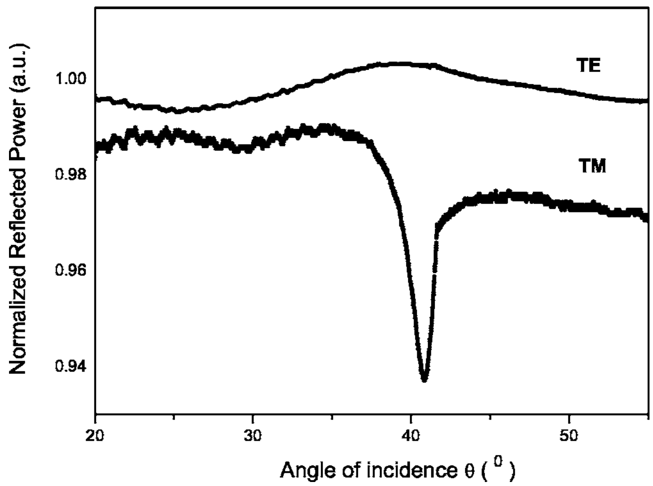

FIG. 2. Reflected intensity as a function of the incident angle θ for TE and TM polarizations for the experimental configuration shown in Fig. 1. SPP resonance is observed for TM polarization only.

scanning the angle of incidence and monitoring the reflected power, excitation of SPP can be observed.

The sample was illuminated with a linearly polarized HeNe laser at the wavelength of $\lambda=632.8$ nm. The angle was scanned with computer controlled motorized stage with a step size of 0.005° and the reflected power was measured with a silicon photodetector. The experiment was performed for both TE and TM polarizations. Due to the well known SPP properties, only the TM polarization can be excited.[5] As shown in Fig. 2, there is a minimum in the reflection of the laser at specific angle. The coupling efficiency is on the order of 5%. We did not try to optimize the thickness of the metal film to excite the SPP with higher coupling efficiency. The resonance angle is $\theta=40.80°$ and the periodicity of the grating is $\Lambda=825$ nm. We calculate the corresponding effective index of SPP to be $n_{\mathrm{SPP}}=1.42$. We note that this effective index is higher than that of the SPP that can be excited at the metal-air interface and is lower than the effective index of SPP that can be excited at metal-PDMS interface.

As is clear from Eq. (1), dielectric functions of the both dielectric medium and the metal film can modify the effective wave vector of the SPP. In addition, for the case of grating-based excitation of the SPP, thickness of the metal layer and the corrugation on the metal surface change the dispersion curve. However, this is not the case in our approach. We feel that in our configuration, the shift in the effective index of the SPP is due to local perturbation on the SPP. At the contact region between the elastomeric grating and the metal surface, there is no single interface. The interface is made up of a succession of PDMS-metal and air-metal interfaces. Instead of two SPP modes corresponding to metal-air and metal-PDMS interfaces, the periodic succession of different interfaces supports a single effective SPP mode.

In order to further clarify the influence of the elastomeric grating, we perform an experiment using the ATR configuration. In this configuration, a 60° equilateral prism with a refractive index of $n=1.765$ is successively coated with 5 nm thick Ni and 45 nm thick Au metal films. Metal surface is illuminated with TM polarized He–Ne laser beam from the prism side, the angle of incidence is scanned, and the reflected power was measured. The experiment was performed with and without the PDMS grating stamp on the metal surface as well as with a PDMS slab without a grating (see inset in Fig. 3). In Fig. 3 we present the ATR device configurations and the angular dependence of the reflected power for each case. Here α is the angle between the laser and the normal of the equilateral prism surface, see Fig. 3(a). The first experiment [Fig. 3(a)] was designed to observe the SPP at the air-metal interface and the measured refractive index of the SPP was found to be 1.05. In the second configuration [Fig. 3(b)], a PDMS stamp with a grating is placed on the metal surface. The SPP occurs at the metal/PDMS stamp interface and the resonance peak is observed at an angle higher than the resonance angle of the previous case. In the third case [Fig. 3(c)], the PDMS stamp is replaced with a PDMS slab without a grating, making conformal contact with the metal surface. The angle, at which the SPP is excited, is much higher angle corresponding to a SPP refractive index of $n=1.55$.

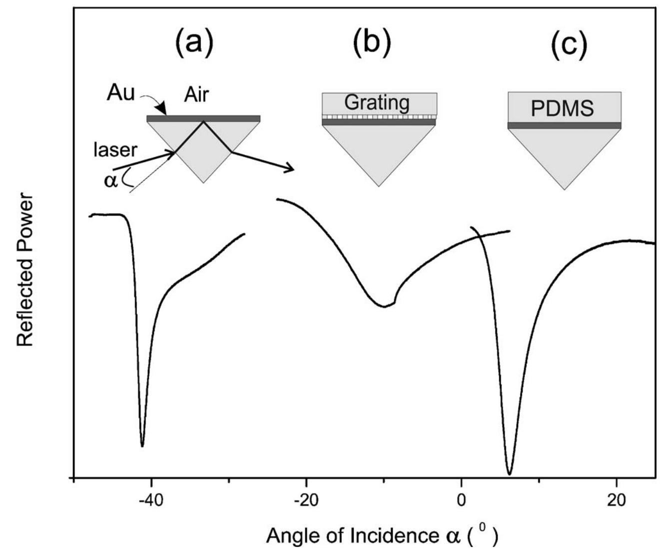

FIG. 3. Reflected intensity as a function of the coupling angle α for (a) air, (b) PDMS grating, and (c) PDMS slab as a upper dielectric medium. Ray configurations are the same in all cases. Dips correspond to SPP resonances.

As seen in Fig. 3(b), distinct SPP modes expected at the air-metal and PDMS-metal interfaces are not observed and instead a broad resonance peak appears. Finally, we point out that the effective refractive index of the SPP calculated from this measurement is consistent with our previous measurements when the method of measurement and the refractive indices involved are properly taken into account.

In the present experiment, we replicate a ruled grating structure. Due to the triangular shape of the ruled grating PDMS grating stamp can be expected to partially collapse during conformal contact with the metal surface. Effective index of the grating structure depends on the fill factor of the grating. Figure 4 represents the model of the structure with the grating in contact with the metal surface. This so-called binary grating can be modeled by using the rigorous coupled wave analysis (RCWA).[11] The resulting effective index can be calculated using Rytov's equation which for TM polarization can be approximated as

$$\frac{\Lambda}{n_{\mathrm{eff}}^2}=\frac{d}{n_1^2}+\frac{\Lambda-d}{n_2^2}. \quad (3)$$

In Eq. (3), $n_{\mathrm{eff}}=1.42$, is the overall effective index of the SPP mode propagating in the structure and $n_1=1.55$ and n_2

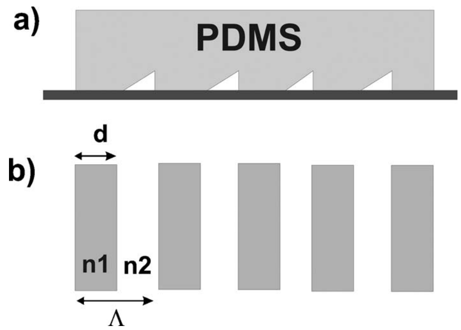

FIG. 4. (a) Partially collapsed PDMS grating on the metal surface. (b) Schematic of the effective index model used in the RCWA calculation.

$=1.05$ are refractive indices of the SPP at the PDMS interface and air interface, respectively. d is the width of the PDMS region and Λ is the period of the grating. Using the above equation we calculate d to be 690 nm upon contact.

We note that we could not observe the plasmon polariton on the metal-glass interface with the PDMS grating in the reflection measurements. A similar lack of observation had earlier been made for singly corrugated metal surfaces.[12] Absence of the SPP for the surfaces facing away from the incident side was explained to be due to a lack of corrugation on these surfaces. Further analysis[13] suggested that for singly corrugated surfaces, light diffracts at the corrugated interface and is absorbed in the metal film until it reaches the metal-glass interface to only weakly excite the SPP. Also diffracted light from grating surfaces cancels each other. We belive that in present case the reason for the lack of coupling is due to the absorption of the metal film.

In conclusion, we introduce a novel technique to excite a SPP mode on a slab metal surface. This approach eliminates the need for a prism or the fabrication of a corrugation on the metal surface to match the momentum of the light to that of the SPP. Due to its compatibility with microfluidic integration, this technique may find use in biosensing applications.

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