Active Plasmonics

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Abstract: We suggest, numerically model and present initial experimental results on a new concept, based on a nanoscale structural transformation in a plasmon waveguide material, which enables optical, electronic and plasmonic modulation of surface plasmon-polariton signals.

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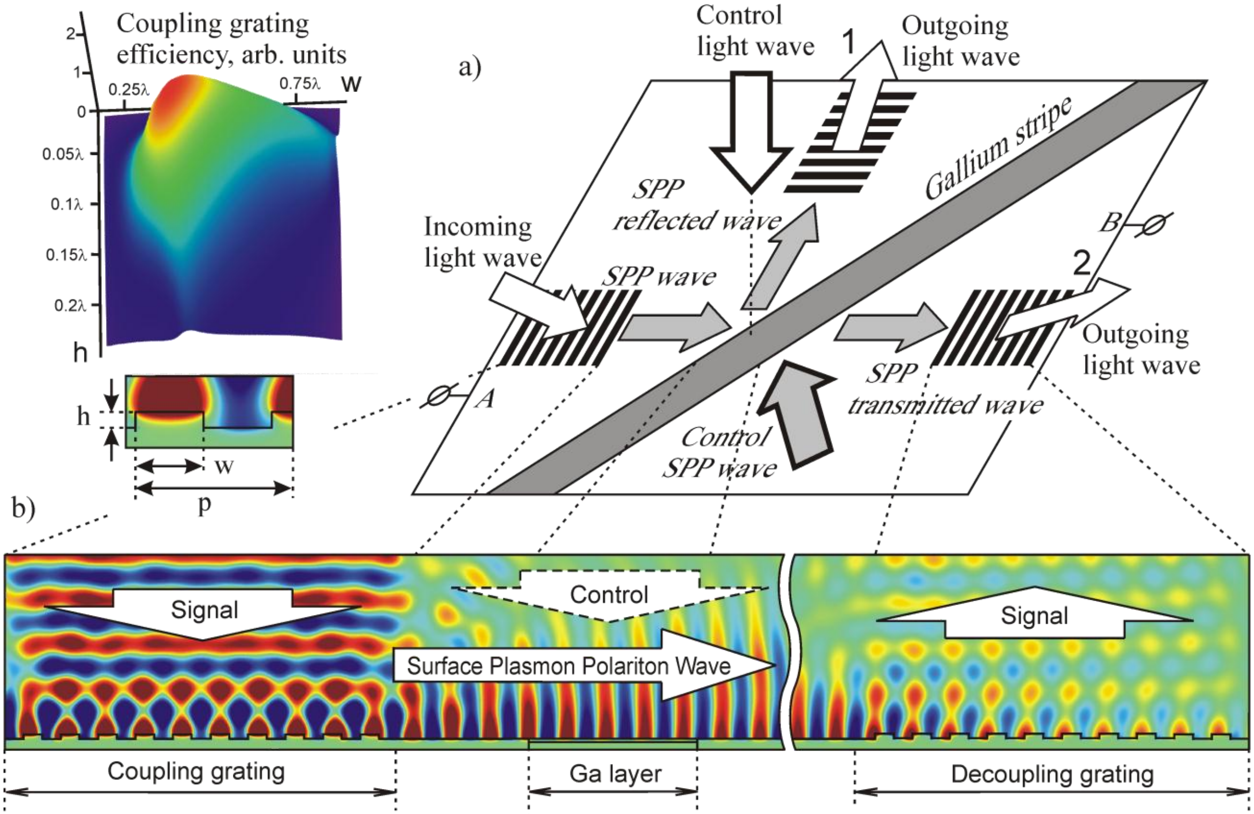

Fig 1. (a) Generic arrangement for a surface plasmon-polariton (SPP) device offering the functionality of optical, electronic and plasmonic modulation of SPP's; (b) Results of finite-element modelling showing a cross-section of the electromagnetic fields in the device. The inset shows the coupling efficiency of the gold-silica grating as a function of grating height *h* and pitch *w*.

Surface plasmon-polaritons (SPP's) are electromagnetic waves coupled with electron oscillations at a dielectric/metal interface. Passive guiding and routing of SPP's are topics that now attract considerable attention as SPP's are perceived as potential high-bandwidth information carriers for future highly-integrated photonic devices. Here we introduce a new concept for *active switching* of SPP's based on control of the waveguide's material properties. Our approach takes advantage of the most characteristic features of SPP's, namely that their propagation depends strongly on the metal's properties in a nanoscale layer at the interface where SPP waves are localized. This localization may be exploited if one can control the dielectric characteristics of the interface layer. We propose that such a change may be achieved through a reversible nanoscale structural transformation at the interface.

A generic arrangement for an SPP switch based on this principle is presented in Fig. 1. In this device, the SPP signals propagate on a metal/dielectric interface (e.g. a gold/vacuum). The input optical signal is converted into an SPP wave by a grating and this then propagates towards decoupling grating #2. Between the input and output gratings there is an 'active strip' of material with dielectric properties that may be switched, for example, between those of a metal and those of a semiconductor. If the strip is in metallic form, the SPP signal propagates across it without disruption. If it is in semiconductor form, its transmission is suppressed due to losses in the strip and a reflected signal, decoupled by grating #1, appears due to the impendence mismatch between the waveguide metal and the strip.

Elemental gallium appears to be a suitable material for the use in the active strip [1, 2]. It has a semiconductor-like crystalline phase (known as α-gallium) and an amorphous metallic liquid phase. The transition between these two phases occurs through the reversible growth of a skin layer of the metallic phase from the surface and, as the energy difference between the phases is only 60 meV/atom, it can be achieved by moderate electron-beam and optical excitation, as well as by temperature.

Opto-SPP modulator. When the gallium layer is excited optically (see the arrow labelled 'control light wave' in Fig.1), the transformation may be achieved through simple light-induced heating. However in addition, gallium presents another mechanism for obtaining the metallic phase, namely a non-thermal transition. Due to localization of photo-generated electron-hole pairs on gallium dimers in the α-gallium phase, absorption of light excites the dimers from the bonding to the anti-bonding state, reducing the stability of the surrounding crystalline cell. The α-gallium cell subsequently undergoes a transition to a new configuration without necessarily achieving the melting temperature.

Electro-SPP modulator. Instead of an external optical stimulation, an electrical voltage applied between terminals A and B (Fig.1) may be used to control such an SPP gate. In this case, the Joule heat released in the gallium section of the waveguide induces the structural transformation in the film.

SPP detector. Recently it was observed that a light-induced structural phase change in a gallium film is accompanied by a change in the conductivity of the film, thus enabling a new mechanism of light detection [3]. A similar principle could be used to *directly* detect SPP waves: energy dissipated by the SSP wave in the gallium layer will change its structural phase and therefore its conductivity, and this may be detected as a change in the resistance between terminals A and B.

SPP-SPP modulator. If the structural phase transition can be induced by energy dissipated by an SPP wave, then all-plasmonic devices are possible. In this case two SPP waves interact on the gallium section of the waveguide: a strong 'control' SPP wave directed towards the gallium section switches the phase of the gallium in the area where the 'signal' SPP passes, thus modulating it (see Fig. 1).

Self-action phenomena. We also expect to see various self-action effects, such as self focusing and de-focusing and self phase modulations in a single intense SPP waves propagating through a gallium section. We also anticipate an SPP analogue of optical bleaching with increasing intensity of the SPP wave propagating through the gallium section of the film, because a gallium layer of increasing thickness is converted into the metallic phase making SPP propagation less lossy. This effect may be useful in *SPP limiters* (analogous to optical limiters).

Numerical evaluation and experimental tests. To evaluate the potential switching characteristics of such SPP waveguides we numerically modelled them using the finite element method. We investigated a gold film waveguide on a silica substrate containing a gallium section of length L. Our calculations revealed that the waveguide transmission depends strongly on the structural phase of the gallium section and that a change in the phase can be used to actively control the transmission. As the structural transformation in gallium is a surface mediated effect, the two phases of gallium may co-exist near the interface, with a thin layer of the metallic phase sandwiched between silica and α-gallium. This makes it possible to continuously, and reversibly control the waveguide's transmission. To analyze this functionality we calculated the waveguide transmission for different thicknesses of metallic gallium and determined that the presence of a metallic gallium layer just d = 30 nm deep can dramatically change the transmission of plasmons through the waveguide.

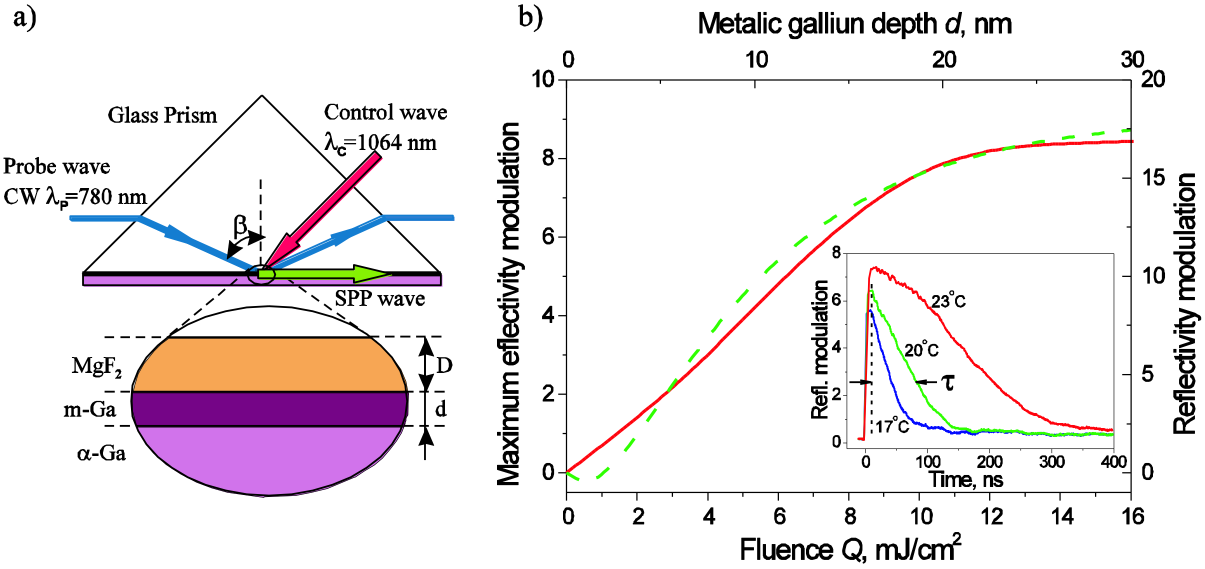

Fig. 2. Experimental tests on controlling SPP's with light: (a) arrangements for pump-probe experiments; (b) Reflectivity modulation as a function of pump fluence at T = 28°C (solid red curve), and the theoretical dependence of reflectivity on the thickness *d* of the metallic phase of gallium (dashed green line). The inset shows the transient dynamics of reflectivity at different temperatures.

We also performed initial experimental tests on controlling SPP's with light. For this purpose we set up reflective pump-probe experiments in the Otto configuration (Fig. 2a). In this experiment the probe beam reflectivity is an indirect measure of the intensity of the SPP wave at the gallium-dielectric interface. The system was configured to provide resonant conditions for SPP excitation in solid gallium. The efficiency of SPP coupling depends strongly on the dielectric parameters of the material so when the pump (control) laser initiates a structural transformation in the gallium it drives the system away from resonance. Such excitation leads to an increase in probe reflectivity. The magnitude of the effect increases with pump fluence up to about 10 mJ/cm^2 and then saturates (Fig 2b, solid red curve). The dashed green curve in the figure shows the calculated dependence of the structure's reflectivity on the depth d of the metallized layer: a fluence Q = 15 mJ/cm^2 corresponds to a depth $d \approx 30$ nm which is sufficient for about 80 percent modulation of the SPP wave in the scheme presented in Fig.2. From here is follows that for a 2.5 μm x 2.5 μm section of gallium waveguide the optical energy required for high-contrast switching is of the order of only 1 nJ. The inset to Fig. 2 shows the transient dynamics of reflectivity, which indicate that the speed of switching depends on the temperature of the interface below the gallium melting point and may be as short as a few tens of nanoseconds.

In conclusion, we introduce and numerically model a new concept for active plasmonics - one based on a nanoscale structural transformation in a plasmon waveguide material. Having identified elemental gallium as a suitable candidate material for controllable active insets in plasmon waveguides, we present the results of initial experiments on its plasmonic switching behaviour.

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