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Thin Plasmonic Grating for All-Optical Switching

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Abstract: We utilize narrow Fano-like resonances in gratings composed of metal films that support long range surface plasmons to provide all-optical switching with low input powers. Switching is illustrated for a grating embedded in chalcogenide glass.

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Long Range Surface Plasmons (LRSP) have extremely long propagation distances and low Ohmic losses and give rise to remarkably narrow, Lorentzian-like, attenuated total reflection (ATR) resonances in the typical prism coupling configuration [1-3] with bandwidths of the order of few Å. Several authors in the past have discussed the application of these narrow resonances to nonlinear optics [4] and all-optical switching in particular [5]. Beside the classical Kretschman configuration, coupling of a LRSP in a thin metal layer is also possible by patterning the metal in a periodic manner so that the LRSP can be coupled through the reciprocal lattice vector of the resulting metallic grating according to the following, standard transverse momentum conservation equation [6,7]:

$$k_{0,x} = \pm k_{LRSP} \mp mG \quad , \quad m = 0, 1, 2, \dots \quad (1)$$

where $k_{0,x} = n_{in} k_0 \sin(\vartheta)$ is the transverse momentum of the incident field. In the following n_{in} is the refractive index of the incident medium, ϑ is the incident angle, $k_0 = 2\pi/\lambda$ the vacuum wave-vector, λ the incident wavelength, $k_{LRSP} = k_0 n_{eff}$ is the wave-vector of the LRSP, n_{eff} is the real part of the effective index of the LRSP calculated for the unperturbed (non-patterned) metal layer as in [7], $G = 2\pi/\Lambda$ is the reciprocal lattice vector of the grating, Λ its period and m is an integer that stands for the different diffracting orders of the grating. In Ref. [7] we have also shown that this kind of coupling gives rise to ultra-narrow reflection resonances with bandwidth that can easily approach $\sim 0.2\text{\AA}$ similar to Wood's anomalies [8]. These resonances, different from the ATR resonances, are strongly asymmetric with a typical Fano-like shape [9-11], moreover their bandwidth is at least one order of magnitude narrower than the corresponding ATR resonances.

We can readily achieve plasmonic Fano-resonances with $Q \sim 10^5$, whereas with conventional dielectric gratings, as the ones studied in Ref.[12] for example, we can have Fano-resonances with Q factors that can reach $\sim 10^4$ at most. Ultrathin, metallic gratings naturally offer these ultra-narrow, Fano-like plasmonic, resonances originated by the coupling of the LRSP with the reciprocal lattice vector of the grating. The geometry we consider: a TM-polarized, monochromatic, plane wave is incident at a generic angle ϑ on a subwavelength, silver grating with thickness d , period Λ and slit aperture a . The silver grating is embedded in a chalcogenide glass (As_2S_3 arsenic-trisulphide). We use chalcogenide glasses because of their large cubic nonlinearity and low two-photon absorption, two characteristics that make them ideal candidates for all-optical switching devices. The dispersion of silver has been taken from the book of Palik while the refractive index of As_2S_3 has been taken equal to $n_{\text{As}_2\text{S}_3} = 2.4$ in the telecommunication band ($\sim 1.5\text{-}1.6\mu\text{m}$). The effective index of the LRSP is very close to the refractive index of the embedding material, As_2S_3 in our case. This is a typical characteristic of LRSPs which is due to the fact that the field of the LRSP is mostly localized in the embedding material reducing therefore the Ohmic losses in the metal and increasing the propagation distance. Once n_{eff} is calculated, we can use Eq.(1) to design the metallic grating for our specific needs. In our case we have chosen the period of the grating $\Lambda = 384\text{nm}$ so to have a coupling of the LRSP with the first reciprocal lattice vector of the grating (G) in the telecommunication band for incident angles in the range between 38° and 48° . Obviously, different frequency ranges and/or different ranges of incident angles can be explored by varying the parameters according to Eq.(1). In Fig.1(a) we show the plasmonic Fano resonance located at $\lambda = 1.55\mu\text{m}$ for an incident angle $\vartheta = 43^\circ$. On the resonance are indicated the wavelengths at which we calculate the nonlinear reflection and all-optical switching in Fig.1(b). The calculation has been performed using the Fourier-modal method (FMM) adapted to the nonlinear case using a mean field theory. The nonlinear refractive index of As_2S_3 is $n_2 = 2.9 \cdot 10^{-18} \text{m}^2/\text{W}$. Switching in the range of few tens of MW/cm^2 input intensity is achievable. For example, at $\lambda = 1.5504\mu\text{m}$ the input intensity at the switching point is $\sim 50 \text{MW}/\text{cm}^2$. Note in particular how the switching intensity decreases if we chose an operative wavelength closer to the reflection peak of the linear Fano

resonance, although in this latter case lowering the input intensity is obtained at the expense of a reduction of the area of the hysteresis cycle. At the peak of reflection of the Fano resonance we get an optical limiting behavior which, in this sense, corresponds to a limit hysteresis cycle with null area.

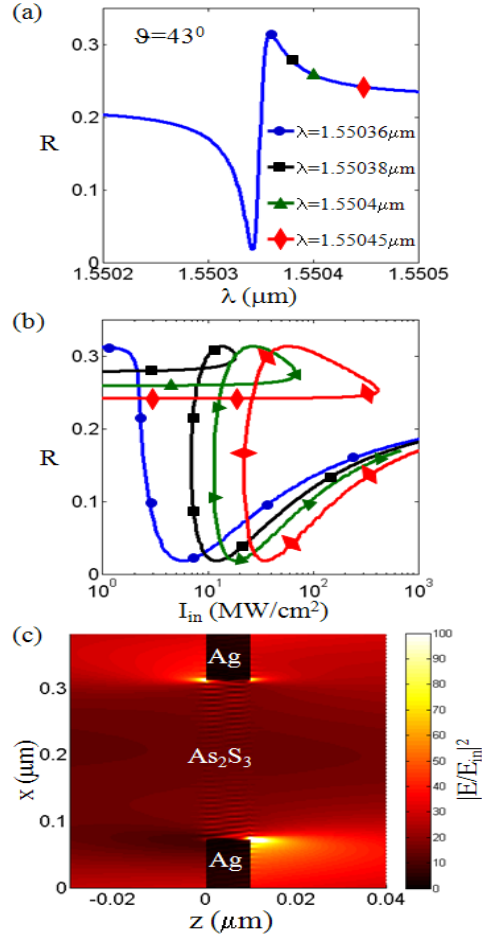


Fig 1 (a) Linear Fano resonance at $\lambda=1.55 \mu\text{m}$ and $\theta=43^\circ$. The marks on the curve indicate the operative wavelengths for the calculation reported in Fig. 1(b). (b) Nonlinear reflection vs. input intensity (I_{in}) at different incident wavelengths as reported in Fig 1(a). (c) Field localization normalized to the incident field at $\lambda=1.5504 \mu\text{m}$ in a region very close to the metal grating.

The input intensity at the switching point is $\sim 50 \text{ MW}/\text{cm}^2$, corresponds to a local field intensity at the switching point $\sim 1 \text{ GW}/\text{cm}^2$. The average field intensity in the region does not exceed the photodarkening threshold of the material.

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