# Optical properties of nano-hole arrays in thin metallic films

**Jill Elliott,[1] Igor I. Smolyaninov,[2] Satoshi Takahashi,[1] Anatoly V. Zayats[1]**

[1]*School of Mathematics and Physics,*
*Queens University Belfast, Belfast BT7 1NN, UK*
*Tel 02890 973941, Fax 02890 973110, Email j.elliott@qub.ac.uk*

[2]*Electrical and Computer Engineering Department,*
*University of Maryland, College Park MD 20742, USA*

**Abstract**: Optical properties of nano-hole arrays in thin metallic films, related to surface plasmon polariton excitations, have been studied. Such nanostructured films reveal strong light-polarisation related effects of the enhanced optical transmission.

## 1. Introduction

Surface plasmon polaritons (SPPs) in a periodic array of subwavelength holes in a metal film have been widely studied, since their discovery, due to their numerous applications in photonic and opto-electronic devices.[1,2] Recent developments in nanotechnology have led to the design of spectral filters and other photonic devices which use SPPs. Surface polaritons are the interaction of photons with collective excitations of conduction electrons close to a metal surface. The coupling of photons and SPPs depends on the wave vector and the frequency as well as the polarisation of the incident light. The polarisation state determines the direction of SPP propagation within the periodic structure. In this paper we present the studies of the optical properties of various periodic subwavelength structures in thin metallic films at normal and oblique illumination with the emphasis on the polarisation related effects.

## 2. Sample fabrication

The samples used in all of the mentioned experiments were fabricated, in house, by magnetron sputtering and are deposited onto glass substrates that undergo a rigorous cleaning process. Focused ion beam (FIB) milling is used to create the nano-hole arrays of the required parameters. By using the FIB we can create cylindrical holes of minimum diameter of about 80 nm and with almost any required periodicity with the overall maximum size of the structures being approximately 75×75 μm$^2$. Shapes such as squares, stripes and elongated holes can also be easily created. Fig. 1 shows examples of a various nanostructures that have been milled onto gold thin films on glass substrates.

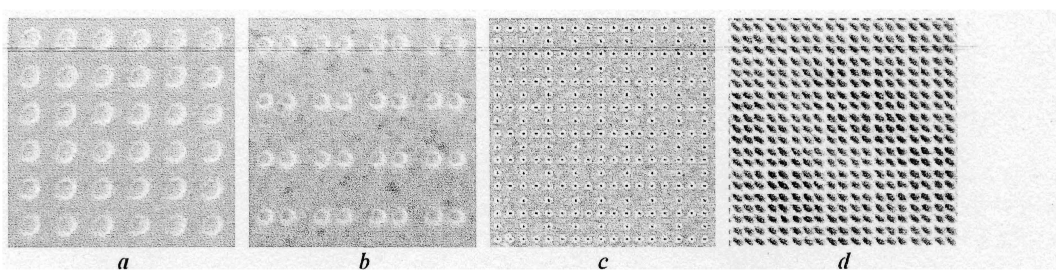

*Fig. 1: Secondary electron images of nano-hole arrays fabricated using focused ion beam milling. The structure parameters are: (a) singlet set of holes – diameter 200 nm, period 600 nm; (b) doublet set – diameter 100 nm, period 500 nm, separation 200 nm; (c) triplet set – diameter 150 nm, period 1200 nm, separation 600 nm; (d) elliptical hole array – long axis of ellipse 500 nm. short axis 250 nm, period 600 nm.*

### 3. Polarisation dependencies of white light transmission spectra of elliptical nano-hole array.

The polarisation dependencies of the enhanced optical transmission through a periodic array of elliptical subwavelength holes in a metal film which is illuminated normally with collimated white light has been studied.[3] The polarisation state of the incident light shows a strong dependence in the transmission spectrum even at normal incidence unlike that of a square array of circular holes which has resonances that are independent of the polarisation state of the incident light. The 20×20 $\mu m^2$ array of elliptical holes (Fig. 1d) were fabricated on a 40nm thick gold film on a glass substrate. The hole parameters are 500 nm (long axis) and 250 nm (short axis) with a periodicity of 600 nm. The transmission spectra obtained were recorded using a spectrometer equipped with a CCD-camera coupled to a long working distance optical microscope. A stabilised white light source is passed through a polariser where it illuminates the sample. An objective lens collects the transmitted light. The transmitted light is passed through an analyser and is coupled to a fibre bundle which is connected to the spectrometer.

The polarisation of the incident light and the depolarisation effects determine the transmission spectrum of an array of asymmetrical holes in a metal film (Fig. 2a). It is seen from the experiment that light of a certain wavelength is depolarised and transmitted through the structure depending on orientation of the incident light polarisation with respect to the array axes. If an analyser is placed in the path of the transmitted light, there is even stronger colour enhancement observed when the polariser and analyser are close to a crossed orientation (Fig. 2b). In this experimental configuration red light is strongly depolarised when the polarisation axis of the incident light is along the hole rows, but when the incident light is polarised diagonally with respect to the array orientation, blue light is strongly depolarised.

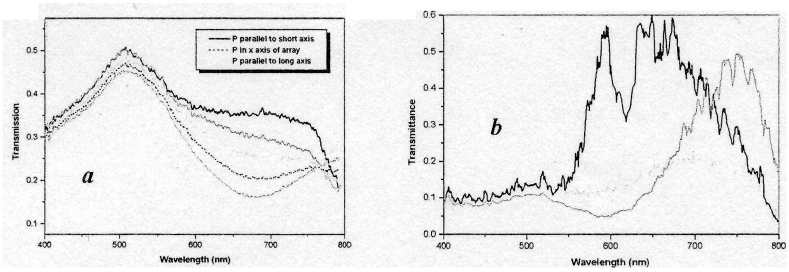


*Fig. 2: (a) Unpolarised transmission spectra of the square array of elliptical hole showing the dependencies on the incident light polarisation orientation with respect to the lattice axes. (b) Polarised transmission spectra measured with the incident light polarisation along the lattice axis: (solid line) transmitted light polarisation is perpendicular to the incident light $\phi=90^o$, (dark and light grey lines) transmitted light polarisation is $\phi=(90+8)^o$ $\phi=(90-8)^o$, respectively.*

### 4. Polarisation properties the transmission of the nano-holes with a chiral overlayer.

A rotation of the polarisation of the light transmitted through a 40×40 $\mu m^2$ array of circular holes, diameter 200 nm and period 600 nm, in a 100 nm thick gold film strongly depends on the thin layer of liquid sucrose that is placed on the film surface. Sucrose consists of chiral molecules that provide the polarisation rotation of the light propagating though it. When such a chiral layer is deposited onto a nanostructured metal film, the effect of the chiral molecules can be coupled with the polarisation properties of the metallic structure related to SPP excitations.

In this experiment, a helium-neon laser (633 nm wavelength), was used to excite SPPs at an oblique angle of incidence using both s and p polarisations of the incident light, which were controlled with a half-wave-plate. The polarisation state of the light transmitted through the structure was analysed. The results (Fig. 3) show that for a clean glass slide and a 2 micron circular hole the chiral molecules have little polarisation-rotational power over the transmitted light, however in combination with the subwavelength hole array, the polarisation state of the transmitted light is significantly changed. The transmitted light becomes elliptically polarised with the orientation of the polarisation ellipse dependent on the chiral layer.

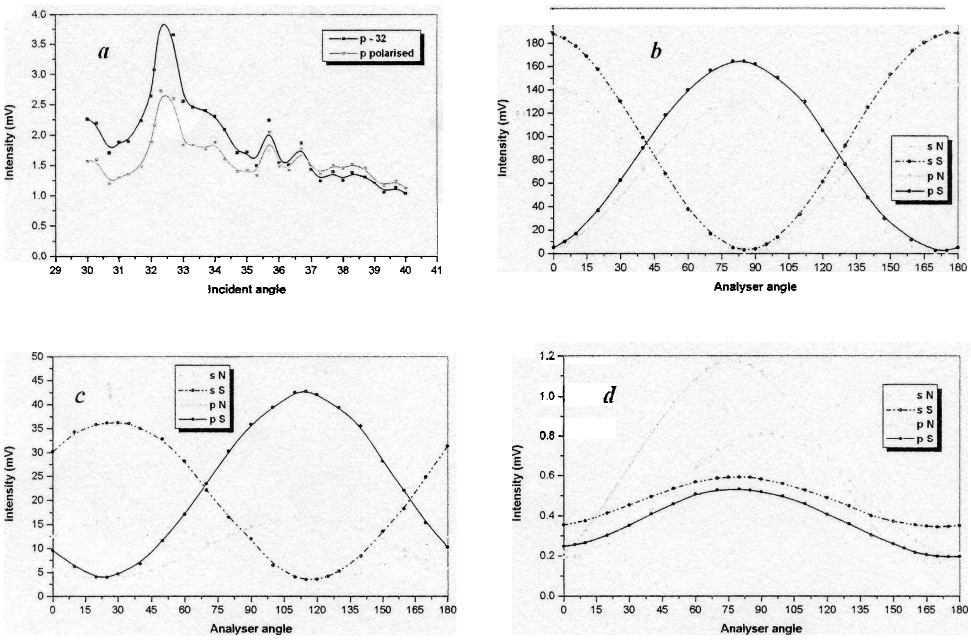


*Fig. 3: (a) Angular spectra of the enhanced transmission through the nano-hole array covered with 70 μm thick layer of sucrose for p and s polarisations of the incident light. (b,c,d) Polarisation dependencies of the optical transmission at the angle of incidence 32°: (b) a bare substrate; (c) a single 2 μm diameter circular hole; (d) the enhanced transmission through an array of 200 nm holes of period 600 nm covered with 70 μm layer of sucrose.*

## 5. Conclusions

In conclusion, we have studied the polarisation properties of the enhanced optical transmission through periodic arrays of nano-holes in gold thin films. The elliptical hole array, under white light illumination, allows the enhanced broadband transmission spectra to be controlled (or tuned) by selecting the polarisation state of the incident and/or transmitted light. The study of the polarisation effects of a thin sucrose layer on the array of holes show that the chiral nature of the molecules within sucrose modifies the polarisation state of the enhanced optical transmission. SPPs in nanostructured thin metallic films offer numerous applications in passive and active optical components and with the observed polarisation dependencies will allow the development of new applications in integrated photonic circuits.

## 6. References

1. W.L. Barnes, A. Dereux, T.W. Ebbesen, Nature, **424**, 824 (2003)

2. A.V. Zayats and I.I. Smolyaninov, J. Opt. A, **5**, S16 (2003)

3. J. Elliott, I.I. Smolyaninov, N.I. Zheludev, and A.V. Zayats, to appear in Opt. Lett., **29**, 15th June 2004 (http://arxiv.org/cond-mat/0310596).