Observation of enhanced transmission for s-polarized light through a subwavelength slit

M. Guillaumée,[1,*] A. Yu. Nikitin,[2,3] M. J. K. Klein,[1] L. A. Dunbar,[1] V. Spassov,[1] R. Eckert,[1] L. Martín-Moreno,[2] F. J. García-Vidal,[4] and R. P. Stanley[1]

[1]*Swiss Centre for Electronics and Microtechnology, CSEM SA, Jaquet-Droz 1, CH-2002 Neuchâtel, Switzerland*
[2]*Instituto de Ciencia de Materiales de Aragon and Departamento de Fisica de la Materia Condensada,*
CSIC-Universidad de Zaragoza, E-50009, Zaragoza, Spain
[3]*Ya. Usikov Institute for Radiophysics and Electronics, Ukrainian Academy of Sciences,*
61085 Kharkov, Ukraine
[4] *Departamento de Fisica Teorica de la Materia Condensada,Universidad Autonoma de Madrid,*
E-28049 Madrid, Spain
*mickael.guillaumee@csem.ch

Abstract: Enhanced optical transmission (EOT) through a single aperture is usually achieved by exciting surface plasmon polaritons with periodic grooves. Surface plasmon polaritons are only excited by p-polarized incident light, i.e. with the electric field perpendicular to the direction of the grooves. The present study experimentally investigates EOT for s-polarized light. A subwavelength slit surrounded on each side by periodic grooves has been fabricated in a gold film and covered by a thin dielectric layer. The excitation of s-polarized dielectric waveguide modes inside the dielectric film strongly increases the s-polarized transmission. A 25 fold increase is measured as compared to the case without the dielectric film. Transmission measurements are compared with a coupled mode method and show good qualitative agreement. Adding a waveguide can improve light transmission through subwavelength apertures, as both s and p-polarization can be efficiently transmitted.

References and links

1. D. E. Grupp, H. J. Lezec, T. Thio, and T. W. Ebbesen, "Beyond the Bethe limit: Tunable enhanced light transmission through a single sub-wavelength aperture," Adv. Mater. **11**(10), 860–862 (1999).
2. H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martín-Moreno, F. J. García-Vidal, and T. W. Ebbesen, "Beaming light from a subwavelength aperture," Science **297**(5582), 820–822 (2002).
3. F. J. García-Vidal, H. J. Lezec, T. W. Ebbesen, and L. Martín-Moreno, "Multiple paths to enhance optical transmission through a single subwavelength slit," Phys. Rev. Lett. **90**(21), 213901 (2003).
4. O. T. A. Janssen, H. P. Urbach, and G. W. 't Hooft, "Giant optical transmission of a subwavelength slit optimized using the magnetic field phase," Phys. Rev. Lett. **99**(4), 043902 (2007).
5. H. Raether, "Surface Plasmons," (Springer-Verlag, Berlin, 1988).
6. J. B. Pendry, L. Martín-Moreno, and F. J. García-Vidal, "Mimicking surface plasmons with structured surfaces," Science **305**(5685), 847–848 (2004).
7. Y. Takakura, "Optical resonance in a narrow slit in a thick metallic screen," Phys. Rev. Lett. **86**(24), 5601–5603 (2001).
8. L. A. Dunbar, M. Guillaumée, F. Leon-Perez, C. Santschi, E. Grenet, and R. Eckert, "F. López-Tejeira, F. J. García-Vidal, L. Martín-Moreno, and R. P. Stanley, "Enhanced transmission from a single subwavelength slit aperture surrounded by grooves on a standard detector," Appl. Phys. Lett. **95**, 011113 (2009).
9. N. Yu, Q. J. Wang, C. Pflügl, L. Diehl, F. Capasso, T. Edamura, S. Furuta, M. Yamanishi, and H. Kan, "Semiconductor lasers with integrated plasmonic polarizers," Appl. Phys. Lett. **94**(15), 151101 (2009).
10. T. Ishi, J. Fujikata, K. Makita, T. Babat, and K. Ohashi, "Si Nano-Photodiode with a Surface Plasmon Antenna," Jpn. J. Appl. Phys. **44**(12), L364 (2005).
11. A. Yu. Nikitin, F. J. García-Vidal, and L. Martín-Moreno, "Enhanced optical transmission, beaming and focusing through a subwavelength slit under excitation of dielectric waveguide modes," J. Opt. A, Pure Appl. Opt. **11**(12), 125702 (2009).
12. E. Moreno, L. Martín-Moreno, and F. J. García-Vidal, "Extraordinary optical transmission without plasmons: the s-polarization case," J. Opt. A, Pure Appl. Opt. **8**(4), S94 (2006).

13. S. A. Kuznetsov, M. Navarro-Cía, V. V. Kubarev, A. V. Gelfand, M. Beruete, I. Campillo, and M. Sorolla, "Regular and anomalous extraordinary optical transmission at the THz-gap," Opt. Express **17**(14), 11730–11738 (2009).
14. F. J. García-Vidal, L. Martín-Moreno, T. W. Ebbesen, and L. Kuipers, "Light passing through subwavelength apertures," Rev. Mod. Phys. **82**(1), 729–787 (2010).
15. M. Guillaumée, L. A. Dunbar, C. Santschi, E. Grenet, R. Eckert, O. J. F. Martin, and R. P. Stanley, "Polarization sensitive silicon photodiodes using nanostructured metallic grids," Appl. Phys. Lett. **94**(19), 193503 (2009).
16. H. F. Schouten, T. D. Visser, D. Lenstra, and H. Blok, "Light transmission through a subwavelength slit: Waveguiding and optical vortices," Phys. Rev. E Stat. Nonlin. Soft Matter Phys. **67**(3), 036608 (2003).

1. Introduction

Light transmission through single subwavelength apertures drilled in a metallic film can be greatly increased by periodically structuring the surface surrounding the aperture [1,2]. The normalized transmission η, defined as the transmission through the structure normalized to the photon flux incident on an open aperture, can be several times larger than unity. This high transmission phenomenon, called extraordinary optical transmission, has been achieved with the so called bull's eye structure, or its one dimensional equivalent, a single slit flanked by periodic grooves on each side [2]. The grooves resonantly couple incident light into surface waves, which constructively interfere with the light directly incident on the aperture [3,4]. The surface waves are either surface plasmon polaritons (SPP) [5], in the case of real metals in the visible and near infrared spectral range, or "spoof SPP" for perfect metals [6]. Both conventional or spoof SPPs are p-polarized waves, i.e. the magnetic field is parallel to the grooves. In the slit and groove case, the absence of cutoff frequency of the fundamental p-polarized slit mode renders possible the excitation of cavity resonances for any slit width [7], increasing further light transmission [3]. As both waveguide resonances in subwavelength slits and excitation of surface waves are p-polarized processes, slit and grooves structures are intrinsically polarization sensitive. This has been advantageously exploited in several studies, for example to filter polarization [8], or to control the polarization state of optical devices [9]. However, most of the s-polarized light is lost. This is a drawback in applications where high throughput is necessary, such as low noise [8], or high speed photodetectors [10].

In order to increase s-polarized transmission, it is first necessary to use a slit width such that it is above the cutoff width. Also, the presence of a thin dielectric layer on top of the slit and groove structure permits s-polarized incident light to couple to dielectric waveguide modes, be directed toward the slit and boost s-polarized transmission. At the same time, p-polarized light is still resonantly transmitted. This scheme was recently proposed and theoretically investigated by several of the present authors [11]. It should be mentioned that the coupling of s-polarized dielectric waveguide modes in a thin dielectric layers have already been considered to enhance transmission, theoretically in slit arrays [12] and experimentally for hole arrays [13]. Although superficially this system may appear similar to the one presented here, they are in fact fundamentally different. In the case of a slit or hole array, the transmission of a periodic structured metal film is considered. Whilst here, we look at the transmission through a single aperture with the goal to harvest light as well as enhance transmission.

The goal of the present paper is to experimentally validate the concept of Ref [11]. A dielectric layer is fabricated on top of a slit and groove structure. The experimental measurements show that a dielectric layer radically increases s-polarized transmission. Comparisons with theoretical calculations are reported. It shows that considering perfect electric conductor (PEC) in theory, as done in Ref [11], still gives accurate prediction for s-polarized light transmission for gold in the visible spectral range as the field is not as tightly bounded to the surface as in case of SPP.

2. Fabrication and optical characterization

Each structure is composed of a single slit with 7 periodic grooves on either side. The grooves are 180 nm deep and 325 nm wide. Both the slits and grooves are 10 µm long. The slit width w and the period Λ are the parameters varied in this study. A 250 nm thin dielectric layer

covers the slit and groove structure. A schematic view of a slit and groove structure covered with a thin dielectric film is shown in Fig. 1(a).

First, a 420 ± 10 nm thick gold film was sputtered onto a clean glass cover slip (thickness ≈150 µm). Slit and grooves structures were milled in the film by focused ion beam (FIB). One of the structures milled is shown in Fig. 1(b). A dielectric layer was then added above the slit and groove structures with the following procedure. 100 mg of Poly(methyl methacrylate) (PMMA) was dissolved in 1 mL anisole ($CH_3OC_6H_5$). The solution was spun onto the gold structure at a speed of 5300 revolutions per minute. This results in a 250 ± 10 nm thick PMMA layer above the metallic structure. This corresponds to the thickness suggested in Ref [11]. Both slit and grooves are completely filled with PMMA. The profile of the PMMA film on top of the structure was measured by atomic force microscopy (AFM). Figure 1(c) shows this profile after averaging over several line scans taken perpendicular to the slit and groove direction. A modulation $x < 25$ nm is measured on top of the grooves, which can be considered as optically flat ($x < \lambda/10$). Above the slit, a modulation of height $h = 100 \pm 10$ nm has been measured. This will have little influence on the optical properties of the structure as $\lambda/5 < h < \lambda/10$.
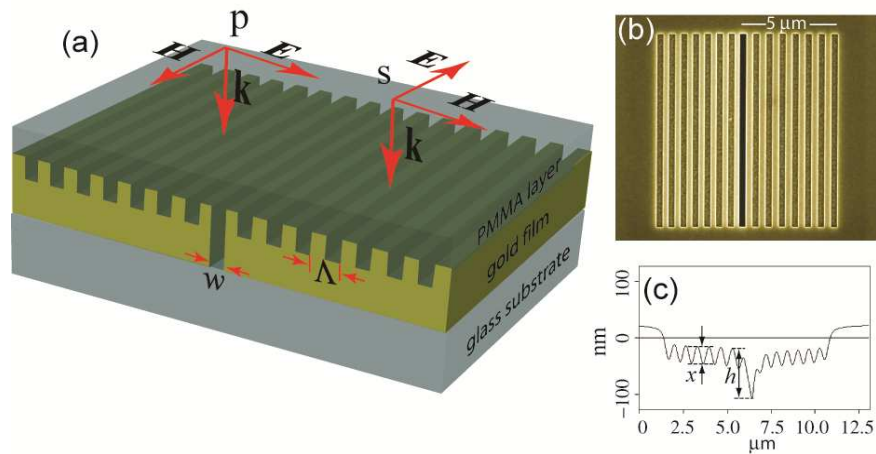

Fig. 1. (a) A schematic of the studied structure and definitions used in this letter for the polarization state and the structure dimensions. (b) SEM image of a slit and groove structure. (c) Profile of the PMMA layer deposited above a slit and groove structure measured by AFM.

Transmission measurements were taken at normal incidence using a halogen light source. The low numerical aperture (NA < 0.1) incident beam is linearly polarized using a Glan laser prism (extinction ratio 10^5). The transmitted light is collected with a microscope objective (NA = 0.6 and power 40 ×) and analyzed with a monochromator and a cooled charge-couple-device camera. The transmission through the structure is normalized to the photon flux incident on the open aperture (i.e. the slit).

In order to validate the experimental measurements, we have performed numeric calculations using the coupled mode method [11]. For simplicity, gold has been treated as a PEC and a fixed dielectric constant $\varepsilon_d = 2.25$ has been used to represent both the PMMA layer and glass film. As a rule, the PEC approximation provides a good semi-quantitative agreement with the experiment for s-polarization in the optical region. For p-polarization the results based on PEC approach are not reliable for wavelengths shorter than 600 nm, but the agreement improves with increasing wavelength. For a discussion regarding the validity of PEC approximation in the optical regime, see Ref [14]. The finite collection angle of the experiment has been taken into account in the calculations by restricting the integration interval of the propagating part of the transmitted angular spectra.

Transmission measurements were first made without the PMMA layer. For p-polarization, high transmission induced by SPP excitation is expected at a wavelength λ close to

$$\lambda_{SPP}^{(n)} = (\Lambda/n)[\varepsilon_d \varepsilon_m/(\varepsilon_d + \varepsilon_m)]^{1/2}$$ where n is an integer indicating the SPP order, ε_m and ε_d are respectively the dielectric constant of the metal and the dielectric medium at the interface with the metal (in the present case air) [1,2]. As $\lambda_{SPP}^{(n)}$ scales with Λ, the transmission peak is red-shifted on increasing Λ. This is what is seen in Fig. 2(a) for $w = 311$ nm, where the high transmission peak ($\eta \approx 1$) measured at $\lambda \approx 725$ nm for $\Lambda = 600$ nm shifts to $\lambda \approx 800$ nm for $\Lambda = 680$ nm. In the s-polarization case, the transmitted spectrum is independent of period [Fig. 2(b)] since no surface waves are resonantly excited. At wavelengths larger than the cut-off wavelength λ_c, the fundamental slit mode for s-polarization is evanescent, inducing a transmission reduction [15,16]. $\lambda_c = 2w\varepsilon_d^{1/2}$ for perfect metals. λ_c is slightly larger in the case of real metals due to their finite conductivity [16]. For $w = 311$nm, the transmission drops for $\lambda > 700$nm. Decreasing w reduces the transmission [15], as is shown in Fig. 2(c). Measurements are in good agreement with the calculated spectra.
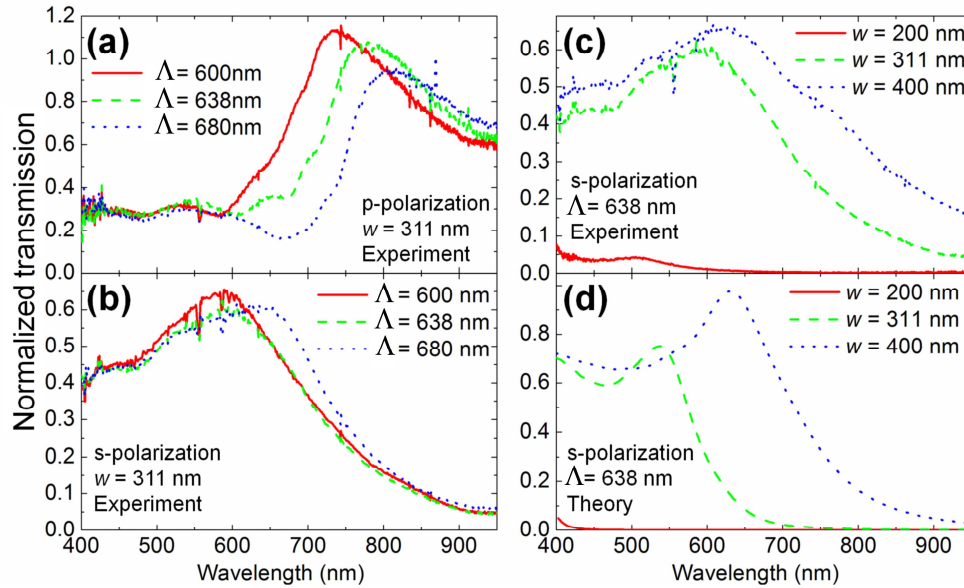

Fig. 2. Normalized transmission spectra of slit and groove structures milled in a 420 ± 10 nm thick gold film. Each slit is flanked by 7 periodic grooves 180 nm deep and 325 nm wide. Both slits and grooves are 10 µm long. Measurements for (a) p-polarization and w = 311 nm, (b) s-polarization and w = 311 nm, (c) s-polarization and Λ = 638 nm. (d) Theoretical calculations from the coupled mode method for the same parameters than (c).
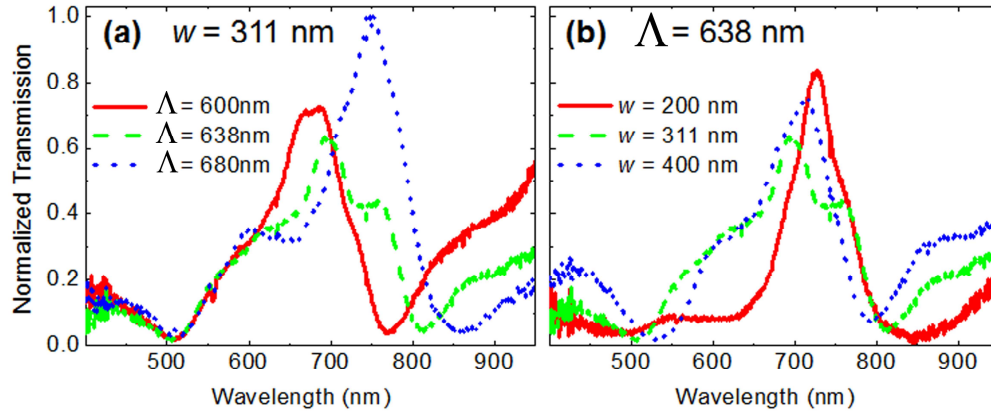
Fig. 3. P-polarized transmission spectra measured for slit and groove structures covered by a thin dielectric layer. The slit and groove dimensions are the same than for Fig. 2. In (a), w = 311 nm; in (b), Λ = 638 nm.

The p-polarized light transmission through the structures covered by the PMMA layer is shown in Fig. 3. As already observed in Fig. 2(a), the transmission peak in Fig. 3(a) is shifted as the period is increased, which is characteristic of the resonant transmission induced by surface wave excitation. $\lambda^{(n)}_{SPP}$ is red-shifted as compared to the air case due to the presence of the PMMA layer. Consequently, the transmission peaks observed in Fig. 2(a) are displaced to longer wavelength. In Fig. 3, these peaks are out of the wavelength range considered and therefore not observed. The peaks observed in Fig. 3 are attributed to the excitation of $\lambda^{(2)}_{SPP}$.

Transmission spectra for s-polarization with a dielectric layer added on top of the metal are shown in Fig. 4. The dielectric layer modifies the transmission properties of the structure, as expected from Ref [11]. Spectra are now dependent on periodicity. This indicates that the metallic grating allows incident light to resonantly couple into the dielectric layer. This coupling occurs at $\lambda^{(n)}_w = (p/n) q_w$, where q_w is the effective index of the waveguide mode. Note that in the 250 nm dielectric layer, only one s-polarized waveguide mode is supported in the wavelength range considered [11]. High transmission peaks are measured, showing that the dielectric layer is acting as a waveguide and efficiently couples light through the slit.

The highest transmission measured is $\eta = 2.5$ for $\Lambda = 680$ nm. At $\lambda \approx 800$ nm, this corresponds to a 25 times increase as compared to the s-polarization case without PMMA layer. Due to the finite numerical aperture of the objective used in the measurement, part of the light is not collected. The amount of light that is effectively transmitted through the slit is consequently higher than what is measured.

The cut-off wavelength is increased as the slit is loaded with PMMA. This increase is however not sufficient to efficiently transmit light in the case of the 200 nm wide slit; see Fig. 4(c). Even if the incident light is resonantly coupled into the waveguide mode, light is not transmitted for w = 200 nm as the slit mode is evanescent and thus does not allow high transmission for a 420 nm thick film.

Theory predicts twice the measured transmission [see Figs. 4(b) and 4(d)]. This quantitative discrepancy may be due to several reasons such as sample imperfections (e.g. PMMA layer flatness, gold roughness and structure profile) and PEC approximation in the calculations. In Figs. 3 and 4, the spectra measured for the structure with $\Lambda = 638$ nm and w = 311 nm are lower than expected as compared to the spectra measured for other geometrical parameters. This is most likely due to a defect in the PMMA layer as this low transmission was not observed for spectra measured without the PMMA layer (cf. Figure 2).
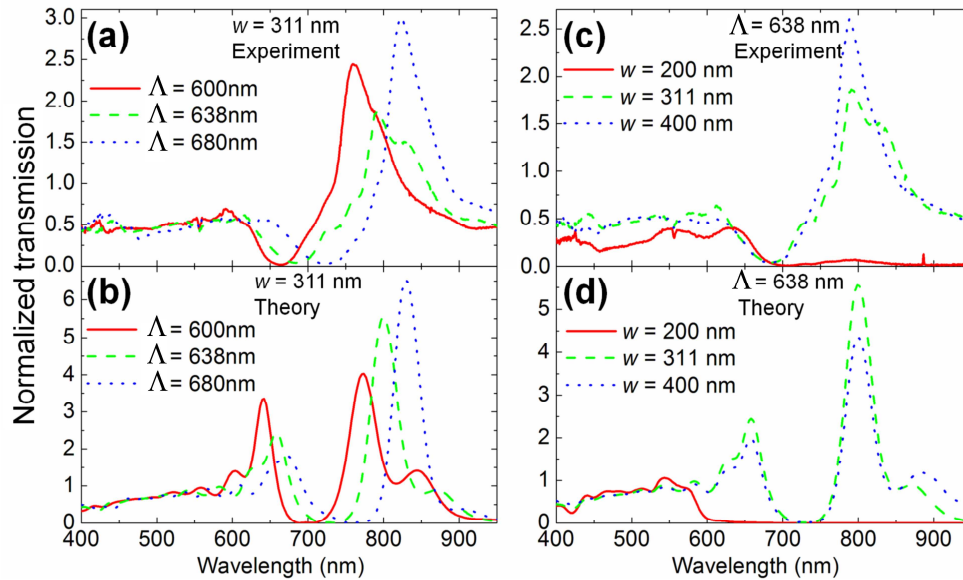
Fig. 4. Normalized transmission spectra of slit and groove structures covered by a thin dielectric layer. The slit and groove dimensions are the same than for Fig. 2. [(a), (c)] s-polarized normalized transmission measurements; [(b), (d)] corresponding theoretical calculations from the coupled mode method. In [(a), (b)], w = 311 nm; in [(c), (d)] Λ = 638 nm.

On the other hand, peak positions for the s-polarization case are predicted very accurately theoretically. This is explained by the fact that $\lambda_w^{(n)}$, which governs peak positions, is weekly affected by sample imperfections and approximations made in calculation. Note that for s-polarized waveguide modes, the field is not as tightly bounded to the surface as in case of SPP. Therefore, approximating a real metal to a perfect one predicts more accurately peak position for s than for p-polarization.

3. Conclusions

In conclusion, extraordinary optical transmission has been experimentally demonstrated for s-polarization. Adding on top of a slit and groove structure a thin dielectric film, which supports s-polarized waveguide modes, efficiently boosts s-polarized transmission. This experiment illustrates the fact that different kinds of surface waves can be used to enhance transmission. Good agreement is observed between experiment and the coupled mode method considering perfect electric conductor used to calculate the s-polarized transmitted spectra. This is explained by the fact that for s-polarized light the field is not as tightly bounded to the surface as in case of SPP. It should be possible to transmit both polarizations at the same wavelength, thus increasing the overall transmission and removing polarization sensitivity. It is particularly important to the applied physics community as it could be used for devices where high throughput is necessary, such as low noise [8] or high speed photodetectors [10].

Acknowledgement