Extraordinary transmission through nano-slits to actively control the optical near-field distribution

A. Ndao[1], Q. Vagne[1], F. Baida[1] and J. Salvi[1]

[1] Institut FEMTO-ST, Department of Optics P.-M. Duffieux
Université de Franche-Comté
16 route de Gray, 25030 Besançon, France
Fax: + 33-381-666-423; email: jerome.salvi@univ-fcomte.fr

Abstract

In this paper we show a true sub-wavelength confinement of the optical near-field thanks to a nanostrucutred metallic film consisting in an array of rectangular nanoslits which support polarization sensitive guided modes. By simply switching the polarization, it is possible to switch on or off subwavelength apertures which are only two hundred nanometers away and thus, to achieve a spatial control of the optical near-field distribution. We use a home made 3D-FDTD code to design the geometrry of our nanostructure and experimental characterizations demonstrate near-field light confinement : these measurements are in good agreement with the theoretical predictions.

1. Introduction

Spatial light confinement is limited by diffraction to approximately half the wavelength of the light field (that is, several hundred nanometers) and yet a large number of applications (data storage, miniaturization of optical devices and light addressing, optical trapping, molecular or nano-probing...) are concerned with a sub-wavelength confinement (smaller than $\lambda/2$). For that purpose a lot of studies suggest to use plasmon resonance (see for example [1],[2]) but Baida [3] recently shows that subwavelength light localization can be achieved (without plasmon) thanks to a guided mode inside nano-apertures engraved in a metallic film. In this theoretical paper, the phase, the amplitude and the polarization of the incident field are controlled in order to successively switch on the 5 letters of the nano-word "FEMTO". The simultaneous experimental control of the phase, the amplitude and the the polarization is very difficult to achieve, so we propose here to limit our experimental study to the spatial control: it is obtained by the excitation of the fundamental mode of a rectangular nano-slit (polarized along the small side of the rectangle) which cut-off wavelength is in the case of a real metal $\lambda_C = 2a + \beta$ [4]: β is linked to the metal dispersion and a is the length of the slit.

2. Description of the sample

The gold film in which the slits are engraved is 100 nm thick and its dispersion is described through a Drude-Lorentz model. The geometry of the slits have been optimized thanks to a numerical method (N-order FDTD algorithm that allows the determination of the structure eigenmodes) in order to have $\lambda_C = 633$ nm corresponding to the wavelength of a usual He-Ne laser. The sample period is chosen in order to avoid Wood and Rayleigh's anomalies in the visible spectral range. The sample scheme is depicted in Fig. 1 and it consists of two primary slits gratings (300 nm period) of horizontal and vertical rectangular slits respectively. The slits are b =50 nm (fabrication limit) wide and $a = 120$ nm long and

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one grating is shifted 150 nm along x and y and rotated of 90 degrees versus the other one. The slits have been fabricated by FIB milling in a 100 nm thick gold layer deposited by evoparation on a glass substrate (a titanium layer of 3 nm has been deposited as an adhesive layer). The whole matrix size is $53 \times 53\ \mu\text{m}^2$ and it is of good quality (see SEM image in Fig. 1)

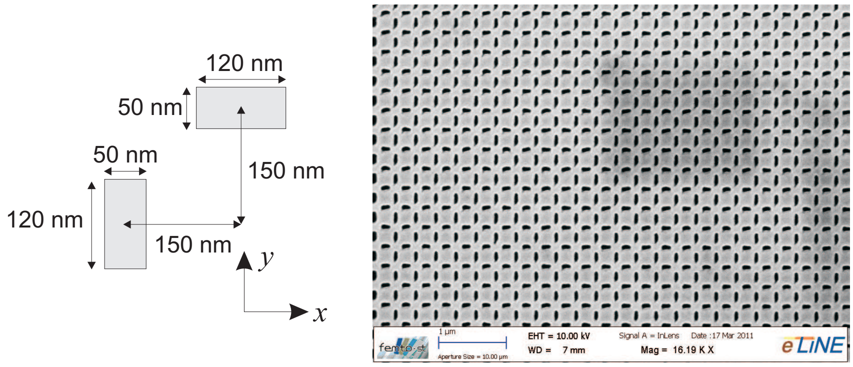

Fig. 1: Scheme of one period of the sample and SEM image of one the fabricated samples on a 100 nm thick gold layer.

3. Optical characterization

The sample described above has been characterized in both far and near field. Fig. 2 (a) shows the experimental and theoretical transmission spectra under normal incidence. The transmission spectra are defined as the ratio of the intensity transmitted through the slits matrix to the intensity transmitted through a squared hole with the same size (i.e. $53 \times 53\ \mu\text{m}^2$). These spectra are polarization independent due to the symmetry of the sample and there is an almost good agreement between theory and experiments. The transmission of the main peak reaches 45%. The discrepancy between the theoretical and experimental curves (peak HWHM and 50 nm shift of the peak position) are mainly due to the non perfect geometry of the real fabricated sample. However, the experimental transmission is suitable for near-field experiments at 633 nm.

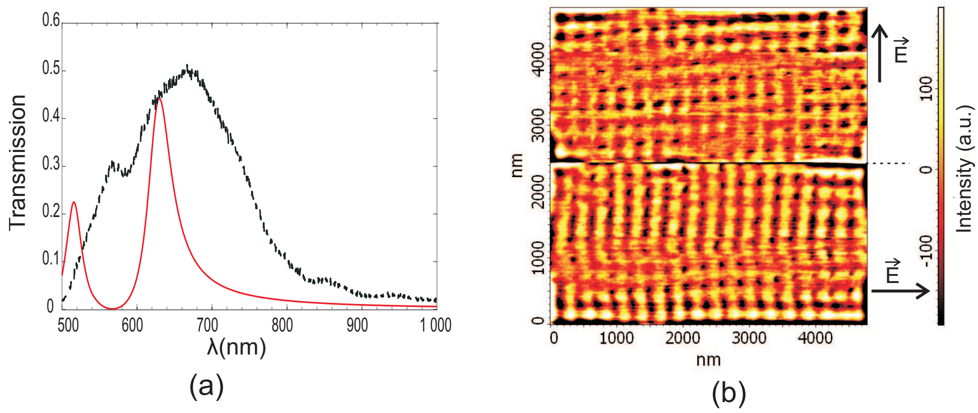

Fig. 2: (a) Experimental (dotted line) and theoretical (solid line) transmission spectra through the sample and (b) near-field image obtained with a SNOM working in transmission mode @ 633 nm. The incident polarization is horizontal in the bottom of the image and vertical in the upper part.

Fig. 2 (b) shows the experimental SNOM images recorded under normal incidence in transmission mode. The incident polarization is switched in the middle of the image (white dashed line) from horizontal (bottom of the image) to vertical (top of the image). The TE_{01} mode being excited for a polarization parallel to width b of the slit, the vertical slits are excited in the lower part of the image and the horizontal ones in the upper part, showing respectively vertical and horizontal lines in the images. The period of these lines is about 300 nm as the period of each primary gratings consisting in vertical or horizontal slits. Moreover hot spots can be distinguished along each line: they correspond to the position of the slits and once again it suits the period of 300 nm.

A zoom-in on the near-field optical image including the polarization switch is shown in Fig. 3. The position of the slits is deduced from the shear force image (not shown here) and it is marked by black rectangles (note the slight angle to the x axis around 5 degrees). One can clearly conclude that dark spots are located above the slits parallel to the incident polarization and bright spots above the perpendicular ones. If the polarization is turned of 90 degrees, bright (respectively dark) slits become dark (respectively bright). The non perfect distribution of the light inside the slits may be related to the difficulty to correctly align the polarization along one edge of the slits (the shear force image reveal a 5 degrees angle between the polarization and the longest edge of the slits) and to the use of a dielectric tip.

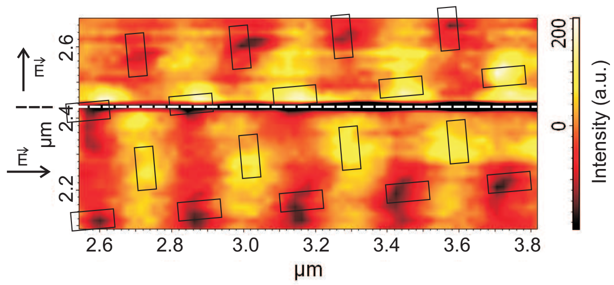

Fig. 3: Zoom-in around the center of the near-field optical image of figure 2. The black rectangles mark the slit positions deduced from the shear force image.

4. Conclusion

In summary, we have demonstrated a very simple way to control the near field of nanostructures by adjusting the linear polarization of the incident field. The experimental optical images clearly demonstrate the sub-λ confinement of light because the nearest slits centers are only around 200 nm away i.e. $\lambda/3$. The control of the spatial distribution is simply achieved through the control of the incident polarization. These kind of nanostructures offers a convenient and versatile way to sub-wavelength light confinement.

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