Mapping of angular and spatial optical intensity distributions issuing from nanostructured slits, milled into subwavelength metallic layers

G Gay, B Viaris de Lesegno, R Mathevet, H J Lezec and J Weiner
IRSAMC-LCAR, Université Paul Sabatier
118 route de Narbonne
31062 Toulouse, France
E-mail: jweiner@irsamc.ups-tlse.fr

Abstract. We present the results of experiments in support of the Composite Diffracted Evanescent Wave (CDEW) model [1] that describes the response of subwavelength planar structures to illumination by polarised plane-wave optical excitation. These experiments consist of four types of data: (1) angular distribution of the transmitted light as a function of quarter-wave groove displacement, (2) efficiency of transmission through a subwavelength slit as a function of slit-groove distance, (3) relative phase measurements by far-field interference patterns of transmitted light as a function of slit-groove displacement, and (4) far-field spatial profile of the optical field intensity issuing from subwavelength slits flanked by periodic grooves and fabricated on a thin metallic layer. These types of structure are of interest for the manipulation of cold atoms by optical potentials near surfaces.

Introduction

Recently the use of micro- and nanostructures to generate magnetic and electro-magnetic fields useful for the manipulation of atoms near surfaces has been widely recognised and is developing rapidly [2]. The interest in optical fields is twofold: first, field gradients of unconventional size and shape can be tailored to capture, trap, and transport atoms, either singly [3] or collectively [4]. Secondly, planar structures can be designed to robustly integrate the capture, cooling and efficient injection of atoms into one- or two-dimensional arrays for use in controlled deposition [5] or for experiments in quantum information [6]. Several research groups are actively investigating the tailoring of these fields based on refraction [7], reflection [8], and diffraction [9]; and because the fields of interest are in the near- or intermediate field regime, it is important to understand the physics of the response of subwavelength structures to optical excitation.

We report here experiments on one-dimensional (1-D) subwavelength slits and grooves milled with a focused ion beam (FIB) into deposited silver layers of about 100 nm thickness. Plane wave radiation impinges on the structures with the phase fronts parallel to the plane of the structures. Grooves of various subwavelength form may be milled on the input side or the output side or both. The basic idea and the prototypical setup for the experiments describe here is shown in Fig. 1. These experiments are designed to test the validity of a model of the optical response, the Composite Diffracted Evanescent Wave (CDEW).
A plane wave impinges on a subwavelength slit that may be flanked with one or many grooves on the left (input) and right (output) surfaces. The output surface is taken to be \( z = 0 \) boundary. Far-field intensity distributions arising from the interference between light propagation directly from the slit and from the flanking grooves can be shaped to provide optical potentials for the capture and transport of cold atoms.

**Summary of the CDEW model**

This model has recently been proposed [1] to explain the response of planar 1-D and 2-D subwavelength structures to plane wave optical excitation. It is based on a solution to the 2-D Helmholtz equation in the near field and subject to slab-like boundary conditions. The basic expression describing wave propagation is

\[
\left[ \nabla^2 + k^2 \right] E(x, z) = 0
\]  

(1)

with \( \nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial z^2 \), \( k = 2\pi/\lambda \) and \( E(x, z) \) the amplitude of the wave propagating in the \( x, z \) directions. Kowarz [10] has written down the solution to this equation for the case of an incident plane wave with amplitude \( E_0 \) and propagation vector \( k_0 \) impinging on a subwavelength slit of width \( d \) in an opaque screen. Specifying the coordinates as shown in Fig. 1, the result for the evanescent modes of the field at the \( z = 0 \) boundary and for \( |x| > d/2 \) is

\[
E(x, z = 0) = -\frac{E_0}{\pi} \left\{ \text{Si} \left[ k_0 \left( x + \frac{d}{2} \right) \right] - \text{Si} \left[ k_0 \left( x - \frac{d}{2} \right) \right] \right\} \quad \text{with} \quad \text{Si}(\beta) \equiv \int_0^\beta \frac{\sin t}{t} \, dt
\]  

(2)

The actual form of the inhomogeneous or evanescent field on the \( z = 0 \) boundary is shown in Fig. 2.

In fact at transverse displacements from the slit \( |x| > d/2 \), the evanescent mode of the field \( E(x, z = 0) \) can be represented by the form

\[
E = \frac{E_0}{\pi} \frac{d}{x} \cos \left( k_0 x + \frac{\pi}{2} \right)
\]  

(3)

that describes a damped surface wave with amplitude decreasing as the inverse of the distance from the slit and a phase shift of \( \pi/2 \) with respect to the propagating plane wave at the slit.
Figure 3. The basic picture of the CDEW model. Incoming plane wave launches composite evanescent waves on the input and output side surfaces. The evanescent modes are reconverted to propagating modes when they encounter the grooves on the output side.

This surface wave is essentially a composite of modes evanescent in \( z \), propagating along \( x \) with \( k_x > k_0 \).

\[
E(x, z = 0) \sim \frac{E_0}{\pi} \frac{d}{x} \int_{-\infty}^{\infty} dk_x \frac{\sin(k_x d/2)}{k_x d/2} \exp(ik_x x)
\]

When the travelling surface wave encounters a discontinuity (groove), a fraction of the intensity is reconverted to the propagating mode \( k_0 \) at the site of the groove. The basic picture of the CDEW model is therefore shown in Fig. 3. An incoming plane wave launches evanescent surface waves along \( x \) (evanescent in the half-space \( z > 0 \)) at both the input surface and the output surface of the slit that, when encountering grooved structures on the output side, reconverts the evanescent modes to propagating modes in the half-space \( z > 0 \). The far field is a superposition of the mode directly propagating through the slit with those "wavelets" originating from the grooves. The composite surface wave exhibits a phase shift of \( \pi/2 \) with respect the directly propagating mode phase at \( x = 0 \). This phase shift is a signature of the CDEW model and should be verifiable in the far field interference pattern.

The quarter-wave phase shift

The \( \pi/2 \) or quarter-wave phase can be investigated by comparing the far field intensity pattern for two types of structures: Type A consists of a periodic array of grooves spaced at some integral number of wavelengths from the slit. Type B is identical to Type A but the grooves are all shifted by a quarter-wave closer to the slit. Type A structures are called unjogged and Type B structures are called jogged. Figure 4 shows an example of two such structures. Jogged structures should exhibit enhanced far-field intensity in the forward direction because the mode directly propagating through the slit and the "wavelets" originating at the grooves are shifted back into phase.
Angular distributions of light intensity

The first set of experiments investigating the far-field intensity measured the angular distributions for jogged and unjogged structures as a function of groove distance from the central slit. A simple goniometer setup, shown in Fig. 5, was used to carry out the measurements. The subwavelength structure is mounted vertically on the rotation axis of a photodiode detector, fixed by a rigid arm at distance of 200 mm from the slit structure. A stepper motor rotates the detector about this axis and the light intensity emanating from the slit-groove structure is recorded as a function of angle. The angular resolution is about 5 mrad. Figure 6 shows a typical measurement and comparison with the prediction of the CDEW model. In this case a 100 nm slit milled in a 250 nm thick Ag film was flanked on each side by a set of five grooves periodically spaced by 830 nm. The nominal distance from the central slit to the first groove was sixteen periods (∼13 µm). No grooves were milled on the input side (source excitation side), and therefore the output side intensity distribution arises entirely from the interference between light directly propagating through the slit and light re-emitted from the groove structures acting as ”antennas” for the surface waves launched at the slit. Comparison between the CDEW prediction (left panel) and the measured distribution (right panel) shows that the CDEW model accounts well for the number and angular spacing of the intensity lobes both for the jogged (black) and unjogged (red) radiation patterns.

Transmission as a function of slit-groove distance

In a second set of experiments the slit-groove structures were set facing the incoming plane-wave excitation and the light transmitted through the slit was measured as a function of slit-groove distance. According to the CDEW picture, surface waves launched at the grooves and travelling inward toward the slit convert to propagating modes at the slit and add to the directly transmitted intensity. This experiment is a test of the survival length of the composite surface wave whose amplitude should decrease as the inverse distance from slit to groove. Figure 7 shows the results of this experiment for the same structures as in the angular distribution measurements, and Fig. 8 shows the CDEW prediction. Comparison of the two figures shows very good agreement. The reason that the unjogged structures all show very small intensity will be explained in a subsequent article.
Phase shift detection by far field interference

In order to measure the phase shift between the directly propagating mode and and the surface wave, we measured the interference pattern arising from a very simple structure: one slit and one groove. We measured far-field angular distribution of the resulting intensity patterns from waves propagating directly from the slit and interfering with the converted CDEW waves at the groove as a function of slit-groove distance. In the forward direction (detector directly in front of the slit-groove structure) the phase dependence of the intensity is given by

$$I = 4E_0^2 \cos^2 (\varphi/2)$$  \hspace{1cm} (5)$$

where $\varphi$ is the phase difference between the waves emanating from the two sources. When the two wave trains are in phase the intensity is maximum, but when they are out of phase by $\pi/2$ the intensity is at the midpoint between maximum and minimum. The results of Fig. 10 clearly show that the jogged structures are in phase and the unjogged structures are out of phase by a quarter wave length.
Spatial profiling

The last of these experiments uses a fluorescing atom flux as a light diffuser to reveal the spatial profile of a highly confined and collimated optical field issuing from a subwavelength slit of thickness \( \simeq 100 \text{ nm} \) flanked by periodically spaced grooves milled on the output side of the planar structure. Similar structures have been shown to produce propagating light, highly confined transversely and "beaming" perpendicular to the structure plane \([11, 12, 13]\). The profiling technique reported here enables the investigation of the beaming intensity distribution as a function of groove parameters, their number and spacing. Figure shows a schematic diagram of the experiment. A thermal oven source heats a Cs metal reservoir to \( \sim 370 \text{ K} \). The Cs atomic beam effuses through an output nozzle, a long narrow tube 36 mm in length, 1.6 mm diameter. The long aspect ratio of the nozzle acts as a rough mechanical precollimator for the atom beam that subsequently passes through a zone of transverse optical molasses \([14]\). Cooling of the atomic transverse velocity components results in a very "bright" \([15]\) Cs atom beam along the \( z \) direction, highly collimated to a divergence < 1 mrad. The optical molasses zone also leads to some slowing and cooling of the longitudinal velocity components. The collimated atom flux then passes in front of and parallel to a planar subwavelength slit structure, illuminated on the back side by a focused laser and from which issues on the front side a highly collimated light field propagating along \( x \), perpendicular to the atom flux. The laser beam is linearly polarised perpendicular to the long axis of the slit. The laser illuminating the slit from the back is tuned over the Cs \( ^2S_{1/2} \leftrightarrow ^2P_{3/2} \) transition producing a fluorescence profile of the intensity distribution issuing from the front side of the planar structure. With the laser tuned to the centre of the resonance line we have measured the fluorescence intensity as a function of laser intensity to ensure that the excitation is always in the weak linear regime and does not approach saturation. The fluorescence is collected by a microscope objective (N.A. 0.28, resolving power 2 \( \mu \text{m} \)) mounted above the plane and, after passing through a polarising beam splitter to filter scattered light from atomic fluorescence, is focused onto a CCD camera. The depth of focus was independently measured to ensure that light collection over the 50 \( \mu \text{m} \) slit length did not degrade the spatial resolution of the optical system. The overall profile resolution is 5 \( \mu \text{m} \) per pixel.
Summary of Results
We have reported here a series of measurements of far-field spatial intensity distributions as a function of various properties of subwavelength 1-D slit-groove nanostructures. The resultant field on the output side of the structures arises from the superposition of a field component directly transmitted through the slit and field components due to the excitation of evanescent surface waves originating at the slit and their subsequent reemission from the flanking grooves. We have invoked a composite surface wave (CDEW) model to explain the results and have measured two key properties of the CDEW wave: the survival length of the composite wave along the surface and the relative phase shift between the composite and the directly propagating modes. Now that the diffractive mechanism operating on these structures has been established we intend to apply them to the manipulation of cold atoms.

References
[1] Lezec H J and Thio T 2004 2004 Optics Express 12 3629-51
[2] Folman R, Krüger P, Schmiedmayer J, Denschlag J and Henkel C 2003 Adv. At. Mol. Opt. Phys. 48, 263-356 and references cited therein
[3] Hill S B and McClelland J J 2003 Appl. Phys. Lett. 82, 3128-30
[4] Rychtarik D, Engeser B, Nägerl H-C, and Grimm R 2004 Phys. Rev. Lett. 92, 173003-1-4
[5] Meschede D, (unpublished)
[6] Mompart J, Eckert K, Ertmer W, Birkl G and Lewenstein M 2003 Phys. Rev. Lett. 90, 147901-1-3
[7] Dumke R, Volk M, Mütter T, Buchkremer F B J, Birkl G and Ertmer W 2002 Phys. Rev. Lett. 89, 097903-1-4
[8] Hinds E A, private communication
[9] Lévêque G, Meier C, Mathevet R, Robilliard C, Weiner J, Girard C and Weebter J C 2002 Phys. Rev. 65, 053615-1-9
[10] Kovarz M W 1995 Applied Optics 34, 3055-63
[11] Martín-Moreno L, García-Vidal F J, Lezec H J, Degiron A and Ebbesen T W 2003 Phys. Rev. Lett. 90, 167401-1-4
[12] Lezec H J, Degiron A, Devaux E, Linke R A, Martín-Moreno L, García-Vidal F J and Ebbesen T W 2002 Science 297, 820-22
[13] García-Vidal F J, Lezec H J, Ebbesen T W and Marin-Moreno L 2003 Phys. Rev. Lett. 90, 213901-1-4
[14] An introduction to the physics of optical cooling and trapping can be found in two special issues of the Journal of the Optical Society of America B. These are: 1985 J. Opt. Soc. Am. B 2 No. 11 and 1989 J. Opt. Soc. Am. B 6 No. 11.
[15] DeGraffenreid W, Liu, Y-M, Ramirez-Serrano J and Weiner J, 2000 Rev. Sci. Instr. 70, 3668-76