Measuring the wavelength-dependent divergence of transmission through sub-wavelength hole-arrays by spectral imaging

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Abstract: We present a study on the far-field patterns of light transmitted through sub-wavelength metallic hole-arrays. Spectral imaging measurements are used here on hole arrays for the first time. It provides both spatial and spectral information of the transmission in far-field. The visibility of the images, measured in two illumination modes: Köhler and collimated, is calculated for different planes in and out of focus. The transmission under collimated illumination reveals that 75% of the beam if non-divergent. The results are in agreement with the low divergence measured by Lezec [Science 297, 820 (2002)].

OCIS codes: (240.6680) Surface plasmons; (120.7000) Transmission

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1. Introduction

The limited diffraction of light through sub-wavelength hole-arrays has been termed an "extraordinary" phenomenon [1] both due to its counterintuitive nature with respect to the conventional diffraction limit of light and due to its potential for applications such as nano-scale lithography [2] and sub-wavelength microscopy [3]. Since it was first reported by Ebbesen [4], periodic hole-arrays have attracted much attention also because of the enhanced transmission through the holes (>1) when compared to the energy that falls on each hole as well as well-defined spectra [4-9].

Hole-arrays have been investigated for their transmission and spectral characteristics, and to a lesser extent for their near-field beam-shapes. The transmission spectra are usually attributed to resonant excitations of surface plasmon polaritons enhanced by the array periodicity [10, 11]. Whereas various theoretical models have been described to characterize the transmission through hole-arrays [12-17], there is still no agreement on the exact mechanisms. Beam shapes have been examined in few studies with a goniometric method and near-field scanning [1] or through the crystallization of photosensitive materials [2, 18].

In this work we study the far-field beam shapes of light transmitted through sub-wavelength metallic hole-arrays by using spectral imaging. Spectral imaging allows one to measure the spectrum of every pixel of an image so that both spectral (λ) and spatial (x, y, z) information is provided. This is in contrast to most of the studies on hole-arrays that measure either a single spectrum or a single image, in which the contribution of light through the entire array or with all wavelengths is integrated.

From a series of spectral images at different focal planes z, the visibility function V is calculated for the relevant wavelength range of the transmission peak. The visibility provides information about the position of the focus and the images reveal information on the divergent angle of the light source. We show that the measured far-field visibility strongly supports low divergence of most of the light transmitted through hole-arrays.

2. Experimental setup

Measurements are performed in far-field by using a wide-field microscope (Leica DM-RXA) to image the sample onto the CCD array of a spectral imaging system. This configuration, shown in Fig. 1, permits us to measure the intensity spectrum ($400 < \lambda < 900$ nm) for every pixel of the image $I(x, y, z, \lambda)$ [19]. The lateral spatial resolution is approximately 400 nm at $\lambda = 500$ nm; at this wavelength, the spectral resolution is $\Delta\lambda = 10$ nm [3]. The spectral images allow us to exclude spectra that originate at imperfections on the metal surface and concentrate on only the relevant spectra that relates to the transmission peaks.

Spectral measurement of the system is based on Fourier spectroscopy with a Sagnac interferometer. The light passing through the interferometer is collimated for all the beams

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that originate from all points of the image. Nevertheless, each point on the image creates a beam that passes the interferometer at a different angle such that the collimated lens in front of the CCD focuses the light on a different pixel of the CCD. In this way, each pixel of the CCD is as a Fourier spectrometer for one point of the image. The optical path difference (OPD) –and with that the recorded wavelength– is changed by rotating the whole interferometer relative to the entrance beam, such that the interferograms for all the pixels are collected simultaneously.

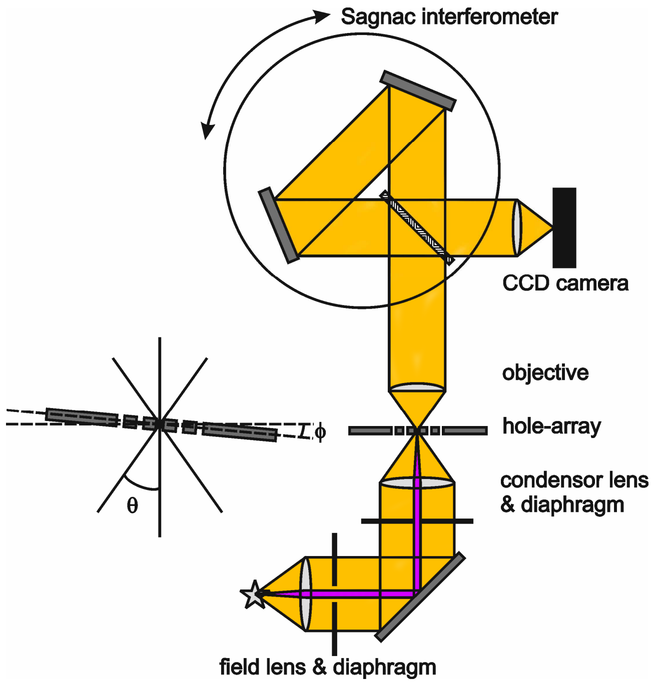

Fig. 1. The experimental set-up. The lower part of the figure shows a conventional wide-field microscope illumination and collection by an objective lens. By closing the condenser aperture the illumination mode is changed from Köhler illumination (orange) to collimated illumination (purple). Instead of a regular CCD camera or spectrum analyzer, a Sagnac imaging interferometer is mounted (SpectraCube, Applied Spectral Imaging) allowing one to obtain spectral and spatial information at the same time. The hole-array is mounted on a (x,y,z) stage, ϕ is the angle between array and optical axis and θ is the angle between illumination and optical axis.

Most of the measurements are performed by illuminating the sample with a collimated beam (shown in Fig. 1 in purple). The angular spread of this plane wave is found to be $-1° < \theta < +1°$. To confirm the capability of our setup to image the individual holes at every wavelength, we also measured the spectral images while illuminating the sample at all possible angles in a range of $-37° < \theta < 37°$. This was accomplished by using Köhler illumination (shown in orange in Fig. 1).

3. Experimental results

The experiments are performed on a square hole-array in a freestanding gold foil with 25 by 25 circular holes, a period of a = 594 nm, a hole diameter of d = 184 nm and a thickness of 200 nm [3]. The hole-array has been mounted so that its normal is aligned parallel to the optical axis ($\phi \approx 0°$). Figure 2 shows typical transmission spectra, which are found after correction for the direct transmission through the foil and for the illumination spectrum. This is done by subtracting the background spectra collected outside the hole-array from the spectra inside the hole-array and dividing by the source spectrum.

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Note that these spectra contain no information about the transmission enhancement (given by the transmission through a hole relatively to the light impinging on that hole with periodic surrounding) which is of interest in other articles (like [4]).

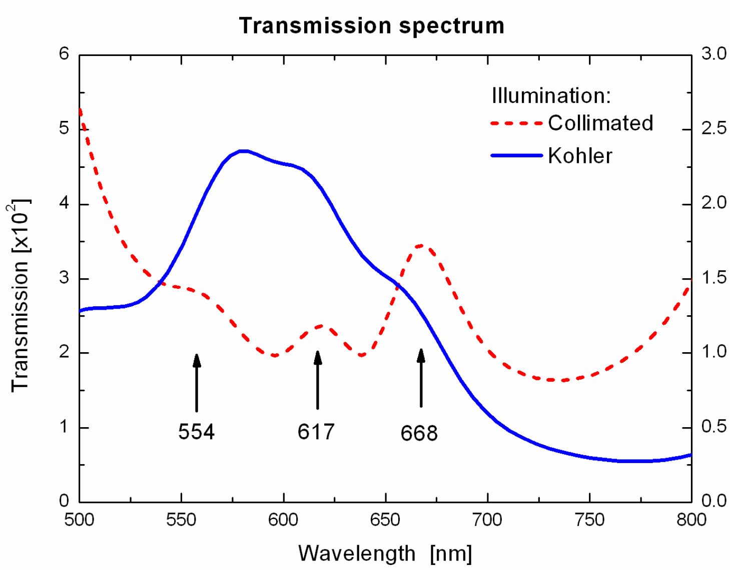

Fig. 2. Transmission spectra of the hole-array for collimated (left axis) and Köhler (right axis) illumination. See text for details.

As expected from the angular dependence of the transmission spectrum and the large angular spread for Köhler illumination, the spectrum measured with Köhler illumination is a broadened version of the spectrum measured with collimated illumination. The three observed peaks indicate that there is an angle of 7° between the illumination beam and the sample (a single peak is expected for $\phi \approx 0°$). The peak positions are in reasonable agreement with dispersion curve calculations (as described in [4]).

We further measured the spectral images in both illumination modes at different focal planes. The zero position (z = 0) is determined by using epi-illumination and measuring the most intense light reflection.

Figures 3(a) and 3(b) show typical images where the spectral images have been integrated over the first peak in spectral range (525 nm < λ < 591 nm) for Köhler and collimated illumination, respectively.

The visibility V of an image is defined as $V = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$ and measures the distinctness of image features [20]. Ideally the visibility ranges from 0 to 1; it is zero for an image with constant intensity and it is 1 if the minima in the image are zero. If each hole diffracts light to a large solid angle, the visibility depends on the point spread function (*PSF*) of the imaging system and the period of the hole-array. If on the other hand, each hole transmits a low-divergence beam (which is equivalent to measuring with a low collection angle), the visibility will significantly decrease. The visibility therefore provides an excellent tool for analyzing in far-field the divergence characteristics of hole-arrays. For a periodic image, the visibility can be accurately calculated from the Fourier-transformed images (Figs. 3(c) and 3(d) by comparing the ratio of the intensity of the side-lobes to the intensity of zero-order diffraction [21]. It should be mentioned that due to the limited numerical aperture of the collection optics, light is collected only from the zero-order transmission through the hole-array. Cases where a first-order diffraction occurs for the transmitted light will not be detected.

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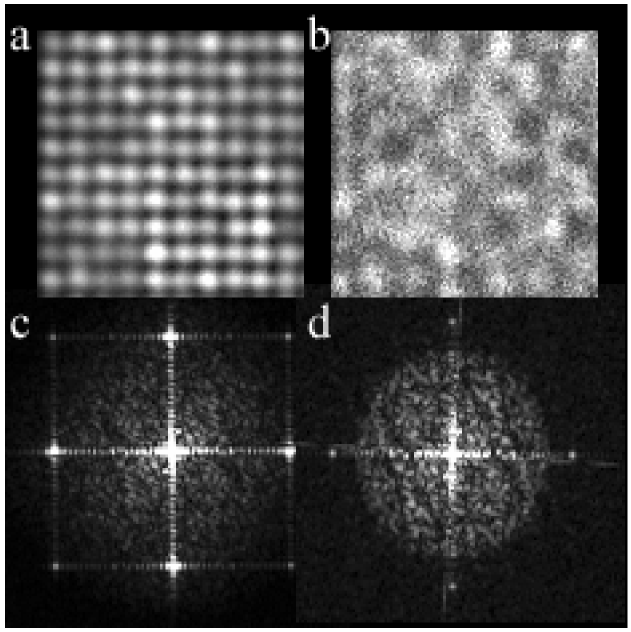

Fig. 3. Images for (a) Köhler and (b) collimated illumination, numerical aperture NA=0.75 for the microscope objective lens. Each pixel in (a, b) is defined by $I\left(x,y,z=z_0\right)=\int_{525nm}^{591nm} I\left(x,y,z=z_0,\lambda\right)d\lambda$. The magnitudes of their corresponding Fourier transforms are given in (c, d).

The visibility as calculated at different focal planes is shown in Fig. 4. The axial position of the visibility peak moves from z = 0.0 µm for the Köhler illumination to a position of z = 0.5 µm for the collimated (plane-wave) illumination. Similar curves are also found when observing the visibility around the other two peaks in the spectrum. With Köhler illumination, light passes through each hole at many different wavelength. As a result, each hole can be viewed as a point-source, and a clear image is achieved when it is imaged on the CCD. The visibility, as expected, is therefore relatively high (0.28). However, when collimated illumination is used, the detected visibility is low (peak visibility of 0.07). This means that the light, which is transmitted through the holes and measured in far-field when plane-wave illumination is used, has a lower divergence and behaves quite differently from a diffracted light wavefront (as measured with Köhler illumination). Lezec [1] measured a similar low divergence, which is in agreement with our measurements.

Figure 4 also shows a model fit calculated by using the *PSF* of our experimental system for the hole-array structure. The model calculates the visibility at each focal plane by taking the appropriate 3D $PSF\left(x,y,z\,|\,\lambda,NA\right)$ [20] and convolving it with the hole-array structure, λ being the wavelength and NA the numerical aperture of the system. The fit is achieved with a single additional parameter that describes a background scatter of 20%. The data indicates that most of the light (75%) is transmitted with no divergence (like a collimated beam that adds only a constant intensity to the whole measured images). Similar results are found also when integrating the spectrum around the other two spectral peaks.

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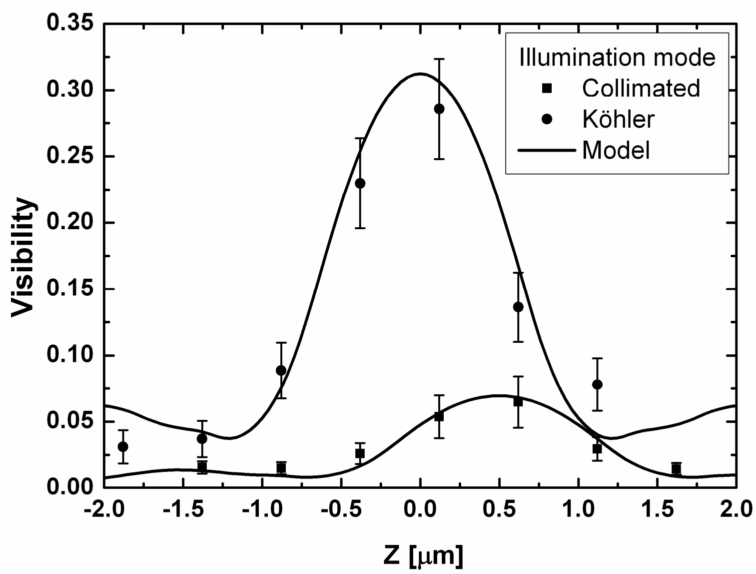

Fig. 4. The visibility calculated for images with intensity integrated around the 554 nm peak by using the Fourier transformed images shown in Fig. 3.

4. Conclusion

We have shown a new method to measure both spectral and spatial information of transmission though a sub-wavelength hole-array. By scanning through focal planes, a set of spectral images is collected. The images can be observed for each of the wavelengths. By selecting the relevant wavelength that corresponds to the transmission peak through the hole-array, a set of images is found. These images are analyzed by calculating the visibility which is a measure for the distinctness of image features. Fourier-transformed images are used to filter out possible noise.

From the visibility measurements with both illumination modes (Köhler and collimated) it is found that 75% of the light is transmitted with almost no divergence. This is in agreement with the low divergence measured by Lezec [1]. In summary, by measuring for the first time the spectral images of metallic hole-arrays and the visibility function, we have shown that the far-field beams resembles plane waves-like propagation.

From the far-field measurements nothing can be concluded about the near-field intensity distribution of the transmission. In further measurements we plan to measure the near-field intensity pattern which is complementary information for analyzing the field distribution of light transmitted through hole-arrays.

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