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Paper

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Published in:

Journal of Physics: Conference Series

Link to article, DOI:

[10.1088/1742-6596/1092/1/012165](https://doi.org/10.1088/1742-6596/1092/1/012165)

Publication date:

2018

Document Version

Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):

Walla, F., Bürkle, F., Sinev, I., Bogdanov, A., Komissarenko, F., Soltani, A., ... Roskos, H. G. (2018). Direct near-field mapping of nano-sphere-excited leaky surface modes at anisotropic metasurface: Paper. *Journal of Physics: Conference Series*, 1092(1), [012165]. DOI: 10.1088/1742-6596/1092/1/012165

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To cite this article: F. Walla *et al* 2018 *J. Phys.: Conf. Ser.* **1092** 012165

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Direct near-field mapping of nano-sphere-excited leaky surface modes at anisotropic metasurface

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Abstract. Leaky surface modes on an ultra-thin anisotropic gold metasurface are directly observed through scattering-type scanning near-field optical microscopy (s-SNOM). Surface modes are excited by focussing light onto a resonant silicon nano-sphere positioned on the surface by nano-manipulation under electron-beam monitoring. The light scattered from the nano-sphere is able to excite surface modes with a broad range of wavevectors. The asymmetric air-metasurface-insulator structure supports a leaky surface mode which is confined at the top interface and leaks into the higher-index substrate. s-SNOM near-field mapping of the leaky surface wave is in good agreement with the results of the full-wave simulations of the electro-magnetic modes on the structure.

1. Introduction

Metasurfaces are two-dimensional periodic arrays of subwavelength elements [1]. Due to strong interaction of the incident light and the subwavelength scatterers forming the metasurface, abrupt changes of optical amplitude and phase can be introduced, which enable the manipulation of the flow of light within ultra-small volumes. Metasurfaces can also be used to guide surface waves, such as surface plasmon polaritons (SPPs). The dispersion of modes on plasmonic metasurfaces can be tailored into the isotropic, elliptical or hyperbolic regimes leading to exotic propagation behaviour of surface waves such as negative refraction, self-collimation and channelling of surface waves [2]. Here, we report on the excitation and direct near-field mapping of leaky surface modes on an ultra-thin anisotropic metasurface by using a resonant silicon nano-sphere for excitation and s-SNOM for mode detection.

2. Methods

s-SNOM combines spectroscopic capabilities with subwavelength resolution down to the tens-of-nanometer scale. This technique is suited for direct mapping of optical surface modes on subwavelength structures. In our experiment, light ($\lambda = 850 \text{ nm}$, $P \approx 10 \text{ mW}$) is focused onto an oscillating cantilever tip which is scanned within the surface near-field region along the sample-air interface. The probing tip thus acts as a nanoantenna, which scatters a part of the electromagnetic surface wave from the near-field into the far-field, where it is detected using pseudo-heterodyne detection.

The sample under study is a periodic array (with square unit-cell size of $(200 \text{ nm})^2$) of gold nano-disks with elliptical base on a fused silica substrate. The lengths of the long and short axes are 175



and 140 nm , respectively, and the thickness of the gold disks is 20 nm . The metasurface is asymmetrically interfaced between air and its fused-silica substrate ($n=1.45$) [3]. Surface waves on the metasurface are excited by shining the focused TM-polarized light onto the resonant silicon nano-sphere which has a diameter of 210 nm and has been placed onto the sample using nano-manipulation techniques supervised by electron-beam microscopy.

3. Results

Figure 1(a) shows the s-SNOM near-field map of the metasurface. The silicon nano-sphere is visible near the centre of the figure (position marked by the dotted red line). The black arrow shows the direction of the incident light parallel relative to the long axis of the metastructure. We attribute the wave pattern, originating from the nano-antenna, to the interference of a surface wave, launched at the sphere, with the incident light [4], while the periodic fine-structure in the picture corresponds to the near-field images of the gold nanodisks. In the picture of figure 1(b), this pattern is removed by Fourier filtering to leave only the wave interference signal. Figure 1(c) shows the two-dimensional Fourier transform of figure 1(b) centred at $k = 0\ \mu\text{m}^{-1}$. Interference fringes are visible as a double ring pattern with an offset from the centre of the image which is equal to the projection of the incident light ($k_{in}\theta_{in}$). For better visibility, the rings are marked with green dashed lines. The radius of the rings represents the wavevector of the surface wave which is found to be isotropic within the uncertainty of the measurement.

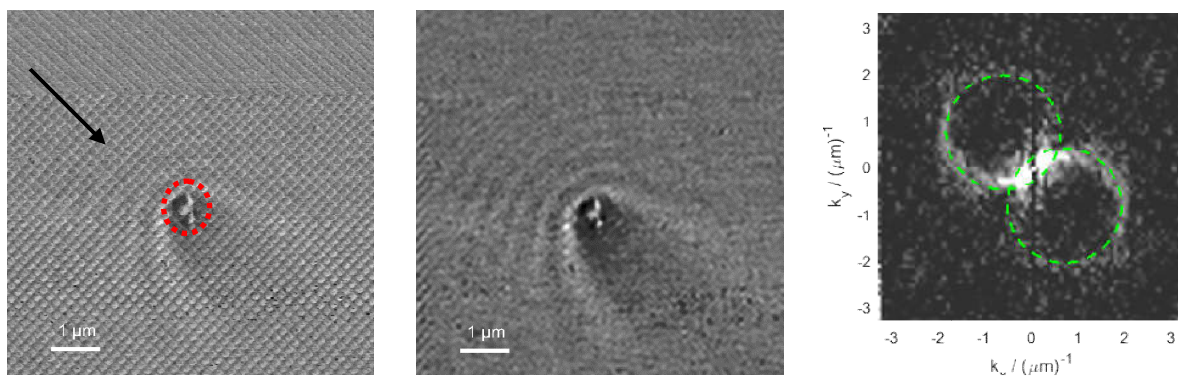


Figure 1. (a) Near-field image of interference fringes between incoming light (black arrow) and the leaky surface wave excited at the nano-sphere. (b) Near-field image after Fourier-filtering to remove the periodic pattern of the gold dots of the metasurface. (c) 2D Fourier-transform of (b), exposing the interference of incoming light with the leaky surface wave as rings with an offset with respect to the centre of the image.

Identification of the leaky mode is supported by full-wave simulations where the nano-sphere is modelled as a discrete electric dipole located slightly above the metasurface. For the given asymmetric interfacing, a leaky surface mode with $\lambda_{sw} \approx 820\text{ nm}$ is found. The wave is confined at the metasurface-air interface, and leaks through the ultra-thin metasurface into the higher-index dielectric substrate.

We thus identify the observed surface mode as a leaky surface mode. Because of its small wavevector ($k_{sw} < k_{in}n$), this mode is not visible in total-internal-reflection measurements, as in [3], while bound modes studied there are not, or only weakly, excited by the nano-sphere under the illumination conditions of our experiment and are thus not identified in the s-SNOM measurements reported here.

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