Modular magneto-optical diffractometer for the characterization of magnetoplasmonic crystals

Ioan-Augustin Chioar,1, a) Richard Rowan-Robinson,1 Emil Melander,1 Tobias Dannegger,1 Sebastian George,1 Björgvin Hjörvarsson,1 Evangelos Th. Papaioannou,2 and Vassilios Kapaklis1, b)
1) Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala Sweden
2) Fachbereich Physik and Forschungszentrum OPTIMAS Technische Universität, Kaiserslautern, 67663 Kaiserslautern, Germany

We report on the development of a modular magneto-optical diffractometer designed to measure the optical and magneto-optical properties of nanostructured magnetoplasmonic crystals. The system uses monochromatic, coherent light beams with defined polarization states, for the energy- and angular-dependent measurement of reflected and transmitted beams. Polarization analysis instrumentation further enables the detailed characterization of the polarization state of the light after the interaction with the magnetoplasmonic crystals. The magneto-optical activity is measured with the help of a quadrupole coil system, allowing for the application of magnetic fields in the plane of the samples. The instrument’s versatile design provides a toolbox of methods capable of capturing a far-field description of the optical and magneto-optical response of magnetoplasmonic crystals. We demonstrate its functionality and utility for the case of a Ni-antidot crystal.

I. INTRODUCTION

The excitation of surface plasmon polaritons (SPPs) in ferromagnetic materials through nanoscale grating coupling has opened up an exciting research playground, where the properties of reflected and transmitted light can be tailored both passively, through the geometry of the imprinted pattern, as well as actively, by the application of magnetic fields.1 This active magnetoplasmonic framework can potentially lead to numerous applications, such as magneto-optical sensors, variable optical attenuators, tunable rotators, etc.2 However, to fully capture and understand the effects of these plasmonic excitations, an in-depth characterization of the properties of the reflected or transmitted light is required. Furthermore, such surface plasmon polaritons arise when a network-mediated momentum matching is achieved between the wavevectors of the plasmon and that of the incoming light, projected in the sample’s plane. Therefore, to properly identify and distinguish these propagating modes from other types of plasmonic excitations, high-precision angular and wavelength-dependent measurements are necessary.3–5

Here, we present an experimental setup designed specifically to excite surface plasmon polaritons while simultaneously detecting and characterizing the polarization state of the reflected or transmitted light, even under the application of a magnetic field. This instrument is highly versatile and capable of fast switching between the various operational modes. Furthermore, light properties can be monitored while changing the angle of incidence and wavelength independently. This ultimately provides detailed two-dimensional maps, which reveal the various grating-coupled plasmonic resonances.

First, the general configuration of the instrument will be presented, detailing each of its components. We will then highlight the various available operation modes, with a main focus on specular reflectivity modes performed with or without the application of a magnetic field. Plasmonic excitations typically manifest themselves through pronounced minima in the reflectivity and our measurements have successfully identified and quantified these effects for a Ni-antidot array, in good agreement with theoretical predictions. We will also briefly discuss other available modes of operation, such as ellipsometric scans, which can potentially offer a more detailed description of the changes induced by plasmons on the polarization state of the light.

II. EXPERIMENTAL SETUP

In the most general case, the setup can be regarded as a generalized diffractometer with polarimetric capabilities. A general schematic is provided in Figure 1 along with a picture of the actual setup in Figure 2. The various components can be grouped into six major categories: the light source, the polarization state generator (PSG), the sample holder system and the goniometers, the polarization state analyzer (PSA), the modulation unit and the detection unit. We shall further detail each of these in turn.

The light source consists of a supercontinuum laser (SC Fianium SC-400-2) incorporating a 3W near-IR seed laser yielding a total power greater than 2W, integrated over a wavelength range spanning from 370 nm to 2600 nm. The output of the supercontinuum is then passed through a single-mode polarization-maintaining optical fiber and into a dual acousto-optical tunable filter (AOTF) system equipped with two RF-driven crystals (AODS 20200-8 by Crystal Technology Inc.) acting as monochromators for the visible (400nm-760nm) and near-infrared ranges (550nm-1100nm). Furthermore, the two free space outputs of the AOTF are, in turn, fiber-coupled to two collimators mounted on the optical table. The spectral power density

---
a) Corresponding author: ioan.chioar@physics.uu.se
b)vassilios.kapaklis@physics.uu.se
FIG. 1. General schematic of the experimental setup highlighting the various components. Some elements may be selectively removed and/or repositioned, depending on the operation mode and the optical properties of interest. In particular, the PEM can be placed before or after the sample, being part of the polarization state generator or analyzer, respectively. For certain scenarios, this swapping can provide complementary measurements, further facilitating the extraction of certain components of the sample Mueller matrix.

After free space emission is larger than 0.5 mW/nm for wavelengths greater than 410 nm. Typically, the visible AOTF crystal (VIS) is operated for the 400nm-700nm wavelength range, while the near-infrared one (NIR1) is employed beyond this point. A long-pass swapping filter system is positioned immediately after the collimators in order to remove any residual harmonics within the measuring wavelength window.

A mechanical chopper is then placed along the beam path, providing amplitude modulation and thus facilitating lock-in detection of the DC signal. A large focal length converging lens is positioned just before the polarization state generator, thus avoiding any unwanted changes that the focusing element might induce on the polarization state of the light before hitting the sample.

The polarization state generator and analyzer each contain a Glan-Thompson calcite polarizer (Thorlabs GTH10M), characterized by an extinction ratio of 100000:1 and a 90% fast axis transmission rate in the optical range. Each polarizer is mounted on a motorized azimuthal rotation stage (Thorlabs PRM1-Z8/M), providing full 360° rotation of the polarization axis in the vertical plane. Furthermore, a Hinds Instruments PEM-100 photoelastic modulator, operating at a resonant frequency of approximately 50 kHz, can be used together with one of the two polarizers. The photoelastic modulator is a periodic dynamic retarder that can play a dual role, acting as a high-frequency modulating agent as well as a polarization state generator/analyzer if operated in conjunction with a linear polarizer having its polarization axis rotated by 45° with respect to the PEM fast axis. Depending on the sequential positioning of these three elements with respect to the sample, as well as the relative azimuthal angle differences between them, information about the different components of the sample Mueller matrix can be retrieved from the DC and the first and second harmonic signals of the PEM.

FIG. 2. Setup photo. Following the beam path, the setup components sequentially reproduce the positions schematically represented in Figure 1. The numbers indicate the various components as follows: 1) the VIS and 1') NIR1 collimators fiber-coupled to the AOTF system (not visible here), 2) the long-pass optical filter system, 3) the chopper, 4) the focusing lens, 5) polarizer 6) the photoelastic modulator 7) the goniometer stage 8) the sample holder system, 9) the analyzer and 10) the detector.

For reflectivity measurements, the sample can be mounted at the end of a vacuum chuck, which is then placed in the middle of a quadrupole air-core coil assembly, as illustrated in Figure 3. In a transmission scenario, the coil-supporting frame is replaced with a back-plate-free skeleton and the sample is suspended in the center of the coil system using a drop-down clamp holder. Facing coils form up pairs, with each pair connected to its own power supply (KEPCO, BOP 75-MG), thus enabling the application of magnetic fields in all directions within the sample plane. This coil system can provide a maximum magnetic field of about ±40 mT in the horizontal and vertical directions, with a magnetic field resolution of ±50 µT within this field range. The entire sample holder assembly is mounted on a goniometer system equipped with two stepping motor controllers (Huber SMC 9000 and 9300) driving a total of six individual motors. Two of these are goniometers that rotate the sample holder and the detector arm around the vertical axis of the sample.
FIG. 3. Close-up showing the reflectivity-mode sample holder attached to the goniometer stage, along with the quadrupole coil assembly. The two translation motors as well as the two cradles can also be observed. The translation motors facilitate the alignment of the sample in the center of rotation, while the cradles are used to ensure the horizontal alignment of the scattering plane.

FIG. 4. Schematics for the setup adapted for operating in standard specular reflectivity and/or TMOKE modes. Since only the total reflected intensity is recorded, the polarization state analyzer can be completely removed and the chopper provides the necessary modulation for lock-in detection.

Finally, the scattered or transmitted light is collected by a photo-detector. Given the wavelength operation window, a biased Si photodiode is typically used (Thorlabs DET100A), the output of which is connected to three Stanford Research SR830 lock-in amplifiers measuring the DC and the first and second harmonics of the PEM signals. A specific LabView user interface has been designed for automated data collection and remote control of the various setup components.

III. OPERATION MODES

Several operation modes are available thanks to the high degree of versatility of the instrument. We will further focus our discussion on reflectivity modes, but we would nevertheless like to emphasize that a complementary description can be achieved by working in transmission.

A. Reflectivity and TMOKE

One of the most simple modes of operation is the so-called standard specular reflectivity mode, which is schematically represented in Figure 4. In this scenario, linearly-polarized light is shun upon the sample surface and the specularly reflected beam is directly recovered by the detector. Both the PEM and the analyzer are removed in this configuration, the chopper becomes the single modulation unit and only the DC lock-in amplifier is employed. This simple operation mode can be used to estimate the total reflectivity of the sample as a function of incidence angle and/or wavelength, thus providing a 2D dependence map. By rotating the axis of the polarizer accordingly, Fresnel reflectivities can be measured for both parallel (p-polarized light) and perpendicular (s-polarized light) polarization alignments with respect to the scattering plane.
(TMOKE) mode, in which case the quantity of interest is
the so-called TMOKE asymmetry, defined as

$$TMOKE = \frac{R(M^+) - R(M^-)}{R(M^+) + R(M^-)}$$  \hspace{1cm} (1)$$

where $R(M^+)$ and $R(M^-)$ represent the reflectivity for
the sample magnetization saturated positively and nega-
tively along the transversal direction, respectively. Practi-
cally, the magnetic field is applied sequentially in both
directions, once the incidence angle and the energy of the
light are set during a scan. This basic operation mode
can be employed to characterize potentially enhanced
magneto-optical activity under plasmonic resonances for
magnetoplasmonic crystals.

**B. Ellipsometric Measurements**

In addition to providing fast and high-precision mea-
surements, the PEM opens up new possibilities for oper-
ating the system, offering access to a wider range of optical
and magneto-optical parameters than the purely polarizer-
based configurations. In fact, the general system config-
uration represented in Figure 1 can theoretically access
15 out of the total 16 elements of the sample Mueller ma-
trix. However, extracting these values from the recorded
intensities can be a complex process and requires several
measurements to be performed, with different values for
the azimuthal angles of the various components as well as
placing the PEM both before and after the sample. Nev-
evertheless, for the simple case of isotropic and non-active
samples, the normalized non-depolarizing Mueller matrix
contains only three nontrivial components, conventionally
denoted by $N$, $S$ and $C$, and takes the following form:

$$M_{iso} = \begin{pmatrix}
1 & -N & 0 & 0 \\
-N & 1 & 0 & 0 \\
0 & 0 & C & S \\
0 & 0 & -S & C
\end{pmatrix}$$  \hspace{1cm} (2)$$

where $N$, $S$ and $C$ are in turn related to the ellipsometric
parameters $\psi$ and $\Delta$:

$$N = \cos(2\psi)$$  \hspace{1cm} (3)$$
$$C = \sin(2\psi) \cdot \cos(\Delta)$$  \hspace{1cm} (4)$$
$$S = \sin(2\psi) \cdot \sin(\Delta)$$  \hspace{1cm} (5)$$

while $\psi$ and $\Delta$ are usually expressed in terms of the
complex reflectivity amplitude ratio, $\rho$:

$$\rho = \frac{r_p}{r_s} = \frac{C + i \cdot S}{1 + N}$$  \hspace{1cm} (6)$$
$$\psi = \arctan |\rho|$$  \hspace{1cm} (7)$$
$$\Delta = \arctan(\rho)$$  \hspace{1cm} (8)$$

where $r_p$ and $r_s$ represent the complex reflectivity am-
plitude for p- and s-polarized light, respectively. We
employ the procedure proposed by Hinds Instruments for
determining $\psi$ and $\Delta$ for $\delta$, which we will also describe in
the following paragraphs.

The time-dependent expression of the intensity recorded
by the detector can be determined by multiplying the
Mueller matrices of the setup components in the order in
which they are placed along the beam path, taking
into account their azimuthal rotation as well (please re-
fer to Chapter 6 of reference5 for a full description of
this derivation). For this, we define all azimuthal an-
gles using a Cartesian coordinate system with the $z$ axis
aligned with the propagation direction and the $x$ and
$y$ axes parallel to the horizontal and vertical directions,
respectively. The polarizers are considered to be ideal
and the wavelength-dependent PEM retardation is as-
sumed to present a harmonic time variation of the form
$\delta(\lambda, \tau) = A_0(\lambda) \cdot \sin(\omega_{PEM} \tau) + \delta_0(\lambda)$, where $A_0(\lambda)$ is the
retardation amplitude and $\delta_0(\lambda)$ stands for the static
PEM retardation. The final intensity expression can be
expanded in terms of the PEM harmonics and further
simplified by operating with a retardation amplitude of
$A_0(\lambda) = 2.4048$, so that the zero order Bessel function
vanishes for every wavelength, $J_0(A_0) = 0$.

The static PEM retardation can be experimentally de-
termined through a calibration procedure which involves
removing the sample and shining the beam through the
polarizer-PEM-analyzer group, with the polarizers axes
aligned and the PEM fast axis at 45° with respect to the
polarizers. In this case, and working still with a retarda-
tion amplitude $\delta(\lambda) = 2.4048$, the ratios between the
PEM harmonics, $V_{1f}$ and $V_{2f}$, and the DC signal, $V_{DC}$
are equal to:

$$\frac{V_{1f}}{V_{DC}} = 2J_1(A_0) \cdot \delta_0 \quad \frac{V_{2f}}{V_{DC}} = 2J_2(A_0)$$  \hspace{1cm} (9)$$

The first ratio can be used to determine the static PEM
retardation for the wavelength window of interest, while
the second one can be used as a calibration tool. If the
ratio $\frac{V_{2f}}{V_{DC}}$ is not precisely equal to the expected result, a
 calibration factor can be introduced which corrects for
the slight deviations.

By setting the polarizer’s axis at an azimuthal angle of
$\phi_{PL} = 45^\circ$, the PEM fast axis at $\phi_{PEM} = 0^\circ$ and
the analyzer at $\phi_{AN} = -45^\circ$, the non-normalized $S$ and
$C$ components, $\tilde{S}$ and $\tilde{C}$, can be computed using the
following expressions:

$$\tilde{S}^{(0)} = \frac{1}{2J_1(A_0)} \left( \frac{V_{1f}^{(0)}}{V_{DC}^{(0)}} \right) + \delta_0 \frac{1}{2J_2(A_0)} \left( \frac{V_{2f}^{(0)}}{V_{DC}^{(0)}} \right)$$  \hspace{1cm} (10)$$
$$\tilde{C} = -\frac{1}{2J_2(A_0)} \left( \frac{V_{2f}^{(0)}}{V_{DC}^{(0)}} \right) + \delta_0 \frac{1}{2J_1(A_0)} \left( \frac{V_{1f}^{(0)}}{V_{DC}^{(0)}} \right)$$  \hspace{1cm} (11)$$

where the (0) superscript is used to highlight the PEM’s
azimuthal angle. The voltage values are assumed to be
proportional to their corresponding Fourier components.
of the detected intensity. Changing the polarizer angle to \( \phi_{PL} = 0^\circ \) and setting the PEM at \( \phi_{PEM} = 45^\circ \) while keeping the analyzer at \( \phi_{AN} = -45^\circ \) gives access to \( \hat{S} \) and \( \hat{N} \):

\[
\hat{S}^{(45)} = \frac{1}{2J_1(A_0)} \left( V_{1f}^{(45)} \right) - \delta_0 \frac{1}{2J_2(A_0)} \left( V_{2f}^{(45)} \right) \\
\hat{N} = -\frac{1}{2J_2(A_0)} \left( V_{2f}^{(45)} \right) + \delta_0 \frac{1}{2J_1(A_0)} \left( V_{1f}^{(45)} \right)
\]

In a non-depolarizing scenario, the sum of the squares of the three components is equal to unity and only one of the two configurations need to be employed. However, it is prudent to assume that this is not generally the case and the reflected beam is partially polarized and characterized by a polarization degree \( \beta \), which can be expressed as:

\[
\beta = \sqrt{N^2 + S^2 + C^2}
\]

Furthermore, expression (2) corresponds to a normalized Mueller matrix, where the normalization is usually performed by setting the first element equal to 1. This implies that the first term of the Mueller matrix will appear as a common factor in the expressions of \( \hat{N}, \hat{S} \) and \( \hat{C} \). Nevertheless, the values for \( N, S \) and \( C \) can be obtained by dividing their corresponding non-normalized expressions by \( \hat{\beta} = \sqrt{N^2 + S^2 + C^2} \). Expressions (6), (7) and (8) can afterwards be used to determine \( \psi \) and \( \Delta \).

IV. RESULTS AND DISCUSSION

In the case of magnetoplasmic crystals, lattice-mediated excitations, such as grating-coupled surface plasmon polaritons, are expected to arise when the following momentum-matching condition is satisfied:

\[
\vec{k}_{pp} = \vec{k}_0(\lambda) \cdot \sin(\theta_{in}) + i \cdot \vec{b}_1 + j \cdot \vec{b}_2
\]

where the \( \vec{k}_{pp} \) and \( \vec{k}_0 \) represent the wavevectors of the plasmon and the incoming light respectively, \( \theta_{in} \) is the incidence angle, while \( \vec{b}_1 \) and \( \vec{b}_2 \) correspond to the reciprocal lattice base vectors associated to the nanopatterned network. For a certain reciprocal lattice vector, defined by a pair of integer indices \( (i,j) \), the same plasmonic excitation can be triggered for certain values of the incidence angle and wavelength of the incoming light. This ultimately translates into a \( \lambda(\theta_{in}) \) dispersion relation specific to each plasmon triggered through this resonant condition, which also bears a dependence on the azimuthal angle of the sample with respect to the plane of polarization\(^3\). Given the possibility to independently tune the wavelength and the angle of incidence with our setup, the different plasmonic modes can be highlighted by pronounced minima lines in the 2D reflectivity map.

To benchmark our setup, we have measured the 2D reflectivity map of a Ni-antidot magnetoplasmic crystal. The sample is a 100 nm Ni thin film, capped with a 2nm layer of Au, which has been patterned into a hexagonal lattice of circular holes, with a typical hole diameter of 275 nm and a lattice parameter of 470 nm, as seen in Figure 5 (for more details regarding sample preparation and characteristics, refer to reference\(^9\)). Given the hexagonal geometry, there are two particular directions of interest, connecting nearest-neighbor \([10]\) an next-nearest neighbor \([11]\) elements.

**FIG. 5.** A schematic representation of the sample surface and the scattering conditions for the specular reflectivity modes, reflecting the geometry of the setup. The hexagonal lattice is reproduced along with the \([10]\) and \([11]\) directions, marked by red and blue arrows, respectively. The inset provides a typical scanning electron microscopy image of the sample topography. p-polarized light is incident on the surface, forming a \( \theta \) angle with the surface normal (optical convention). For TMOKE measurements, a magnetic field \( H \) is applied perpendicular to the scattering plane, as represented by the black arrow.

Figure 6 gives the result of a measurement performed with p-polarized light, in standard specular reflectivity mode, with the scattering plane aligned with the \([10]\) direction. Theoretical predictions computed using a Scattering Matrix Method (SMM)\(^10\) for a model sample are also reported, along with the dispersion relations of certain plasmonic modes occurring within the scanning range. The angle of incidence is varied between 2\(^\circ\) and 89\(^\circ\), as defined using the optical convection, while the energy of the incoming light varies between 1.65 eV and 3.15 eV (751 nm and 394 nm, respectively), thus covering the full optical range.

The qualitative mapping between the experimental and theoretical maps is rather good, capturing the general features and the predicted minima lines corresponding to plasmon dispersions. The marked monotonically-decreasing dispersions correspond to a pronounced decrease in the reflectivity, which is attributed to the excitation of a surface plasmon polariton with a matching \((-1,0)\) reciprocal lattice vector. The measurements reveal an average 10% drop in the reflectivity for this particular mode. However, a strict quantitative comparison with theoretical predictions is limited by lattice inhomogeneities in our sample, such as changes in the orientation of the network’s symmetry axes over larger areas, giving rise to
FIG. 6. a: Theoretical data from SMM showing the specular reflectivity of p-polarized light as a function of incidence angle and energy. The data is rescaled and adapted from ref. 9. The white and black lines denote the dispersions of the different plasmonic modes for the Au/Air and the Ni/Air interfaces respectively. b: Experimental specular reflectivity. In order to facilitate visual comparison and highlight high energies features, both maps presented here give the dependence of the square root of the reflectivity.

c: TMOKE asymmetry angular scan data (grey line) obtained for a fixed wavelength of 636 nm and averaged over 30 tryouts. The reflectivity data (black line), acquired under similar conditions but without the application of a magnetic field, is reproduced for comparison.

less pronounced and broader resonant features compared to theoretical expectations.

Magneto-optical activity has also been investigated using the TMOKE operation mode. An angular scan for a working wavelength of 636 nm is reported in Figure 6, along with the corresponding reflectivity curve measured without any applied field. While the absolute values are rather small, the TMOKE asymmetry presents a sharp change near the local minimum in reflectivity, signaling an enhancement of the tuning of the reflectivity by the application of a magnetic field under plasmonic excitations11,12. Therefore, this method offers the tools for the investigation of the modification of optical properties under applied magnetic fields and in the presence of plasmonic resonances. Also, such measurements hint towards the modification of the dispersion relations of SPPs using magnetic fields11.

In terms of ellipsometry, we have performed a benchmarking scan using an evaporated Au film, with a layer thickness greater than 100nm, thus surpassing the penetration depth within the visible and near-infrared ranges. This facilitates a direct comparison, using the Fresnel equations, with available tabulated data for the complex index of refraction of gold13–16. Following the procedure described above, experimental values for the pair of ellipsometric parameters $\psi$ and $\Delta$ were determined as a function of both incidence angle and wavelength, where the angle of incidence was varied between 6° and 88° and the wavelength between 400nm to 1050nm. The data is shown in Figures 7 a) and b). Furthermore, to ascertain the compatibility of these results with other experimentally-obtained literature values, we have compared them with predictions given by three different tabulated series of complex refractive index values16. Figures c) and d) contain line-cuts through the 2D maps of $\psi$ and $\Delta$ for five wavelength values within the visible range, along with the comparison data. The overall matching is rather good, particularly with more recently published values14,15. The average absolute deviations for each of these wavelengths are below 1° for $\psi$ and below 2° for $\Delta$. With the lock-in technique employed, generally guaranteeing low statistical errors, we attribute the source of the deviations mainly to systematic errors, such as an imperfect alignment of the optical axes of the various components, particularly the polarizer.

V. CONCLUSION AND OUTLOOK

We presented a versatile experimental setup capable of detecting, characterizing and activating nanostructured magnetoplasmonic crystals. This wavelength-tunable diffractometer can be employed in different modes of operation, which can be used to evaluate the impact of grating-coupling SPPs on the optical and magneto-optical properties of the designed surface. We have demonstrated some of its capabilities by providing reflectivity data for a Ni-antidot structure, which is in good qualitative agree-
FIG. 7. Ellipsometry data for a thick evaporated Au film deposited on a glass substrate. a-b) 2D maps reproducing the dependence of $\psi$ and $\Delta$ as a function of incidence angle and wavelength. c-d) Line-cuts through the 2D maps for five different wavelengths (joined data points), $\lambda = (420 \text{ nm}, 490 \text{ nm}, 530 \text{ nm}, 590 \text{ nm}, 660 \text{ nm})$ along with reference values computed by using previously reported data from three different studies\textsuperscript{13–15}. While Olmon \textit{et al}. and Yakoubovsky \textit{et al}. give values for the real and imaginary part of the complex index of refraction for the specified wavelength, the data from Johnson and Christy does not match them precisely. A linear interpolation fit based on their provided values has been nevertheless performed to facilitate comparison with their data set as well.

The modular character of the instrument presented here allows for the study of these effects in terms of polarization dependent reflectivity and ellipsometry. Both yield further important information on the polarization state of the light after reflection or transmission. Such studies will enable a more detailed understanding of light-matter interaction in such nano-architectures and possibly facilitate the design of novel flat optics which will base their operation on the active control of the polarization state of light using magnetism\textsuperscript{17}.

VI. ACKNOWLEDGEMENTS

The authors acknowledge the support of the Knut and Alice Wallenberg Foundation (KAW) project “Harnessing light and spins through plasmons at the nanoscale” (2015.0060), and the Swedish Foundation for International Cooperation in Research and Higher Education (STINT) project “Magnetic Metamaterials”. The authors would also like to thank Dr. Antonio García Martín for the SMM simulations on the Ni antidot structure presented in Figure 6, and Dr. Rimantas Brucas for providing the Au sample used in the ellipsometry measurements.


\textsuperscript{2} N. Yu and F. Capasso, Nature Materials 13, 139 (2014), and references therein.


