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Spectroscopy and imaging of arrays of nanorods toward nanopolarimetry

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Abstract
The polarization dependence of the optical scattering properties of two-dimensional arrays of metal nanostructures with sub-wavelength dimensions (nanoantennas) has been investigated. Arrays of 500 nm × 100 nm gold nanorods covering a 100 × 100 µm² area were fabricated with varying orientations on an electrically conductive substrate. The experimental and computational analysis of the angularly organized nanorods suggest potential use toward the development of an integrated polarimeter. Using the gold nanorods on a transparent substrate as a preliminary system, we show that in the proper spectral range the scattering properties of the structures may be tuned for such an application.

1. Introduction

The coupling of photons and electrons in engineered nanostructures has provided a powerful channel to spatially and temporally control and manipulate the electrodynamic energy. In such structures, where the electrons oscillate in dimensions smaller than the wavelength of the photons, surface plasmon excitation and resonances have facilitated crucial confinement, enhancement, and squeezing of electromagnetic fields in numerous applications. The quest for creating application-specific nanostructures and the necessary tools to probe their characteristics is generating a significant research effort [1–5]. Geometric control at the nanoscale is typically facilitated chemically [6–11], or by nanofabrication techniques [12–15], with the use of electron beam lithography or ion beam milling. Another fabrication process, based on stamp-printing, has also been reported to produce nanoparticle-patterned microstructures [16]. A multitude of geometries is emerging, offering a wide range of field patterns and strengths [17–30], as well as studies on material effects [31, 32] with potential for diverse functionalities. In the particular case of gold nanorods, they have been shown to provide great improvements for two photon luminescence bio-imaging [33, 34] or for resonance shift measurements in living cells [35]. The rod nanostructures have furthermore proved useful in creating metamaterials that exhibit negative refraction in the near infrared [36, 37]. An increasing number of reports on the potential applications of these structures is noted. Zhao et al aptly summarized various uses for remote detection and cancer treatment [38].

In parallel, passive nanophotonic components (such as those not requiring external power for their operation) that are capable of performing analytical functions on their inputs (similar to the traditional electronic devices such as spectrum analyzers, etc) find important applications in integrated optical systems [39–43]. The growing need for integrated optical components necessitates the development of new nano- and micro-scale analytical capabilities such as all-optical modulators [44–48], plasmonic or thermoplasmonic switches [49–52], sub-wavelength metal–semiconductor–metal photodetectors [53], or wireless broadcasting links between a transmitter and a receiver...
Figure 1. Fabrication steps and images of the 400 nm long, 100 nm wide and 40 nm thick nanorods. Initially, a clean glass substrate is coated with 10 nm ITO. (a) Electron beam lithography of spin-coated 120 nm thick polymethyl methacrylate (PMMA). (b) PVD by electron beam of titanium (3 nm) and gold (40 nm). (c) Final lift-off of the PMMA results in the sample patterns. (d) Dark-field image of the six patterned matrices separated by 100 µm in both directions. (e) Scanning electron microscope images of the corresponding patterned matrices in (d) elucidating the individual rods of various orientations.

separated by nano- and/or micro-scaled distances [54]. Nanorods, with their capability to confine and enhance electromagnetic fields [55–57], are suggested here to allow determination of the polarization state of a low intensity beam. The excitation polarization states of nanorods have been treated theoretically [58] and observed experimentally by fluorescence [59, 60] or near-field measurements [61, 62], which have suggested a preferential polarization along the long axis of the nanorods. On-chip evaluation of the polarization state of light remains an important issue that requires miniaturized components to be integrated [63–66]. One can envisage the integration of such nano-components to construct a ‘nanopolarimeter’ either for polarization diagnostics and control or for near-field polarimetry imaging [67, 68]. Likewise, the interfacing of a charged coupled device (CCD), a frame of ordered oriented nanorods, similar to a Bayer filter [69] for color detection, is suggested here to be used for polarization evaluation spectrometry. Furthermore, with emerging application-specific and optimized fabrication technologies [70], an improved antenna response may be achieved that can aid reliable integrated optical nano-circuitry. In this article, we aim to specifically address (1) whether the proposed angularly distributed nanorods can overcome the challenge of obtaining polarization dependence of the response without the need to rotate the excitation polarization, and (2) whether the concept of carrying out polarimetric investigations can be supported by the fabricated nanorods. We therefore begin our presentation by describing the fabrication of the nanorods in section 2. In this section, we also describe (a) the near-field scanning optical microscope (NSOM) configurations employed for the measurements related to the field distribution near the nanorods, and (b) the far-field transmission spectroscopy carried out to determine the overall spectral response of the arrays. The measurements are discussed in section 3, where we also compare the results with the case of metal islands. Here we also provide computational results to support the suggested potential application of the nanorods in polarimetry. Concluding remarks are provided in section 4.

2. Experimental procedure

Preliminarily, using the NSOM, we experimented with a set of fabricated gold nanorods by adapting an illumination through the NSOM tip while rotating the excitation beam’s polarization from 0° (parallel to the nanorod’s major axis) to 90° (perpendicular to the nanorod’s major axis). However, in the plane of the nanoparticles, the intensity of the delivered light was observed to be unintentionally altered as the polarization changed, making it challenging to maintain the same experimental conditions from one orientation to the other. Significant intensity variations can result from the mechanical movements of the polarization optics, slightly changing the fine optical alignment required when an NSOM tip is part of the incident optical path. As a result we designed a dedicated sample that would support an experimental polarization study without the need to modify the incident optical path. Assuming that the NSOM illumination polarization remains unchanged, we designed and fabricated nanorods on the same substrate with various orientations. By rotating the nanorods’ symmetry axis on the sample itself, we could study the polarization dependence of the scattering using a fixed polarization source. This approach required the sample to be mounted such that one of the nanorod orientations would be parallel to that of the fixed illumination source. Conveniently, the 0° array was considered for this purpose.

The fabrication steps are described in figure 1, starting with a 150 µm thick quartz slide substrate coated with
10 nm of indium tin oxide (ITO). A 120 nm thick layer of polymethylacrylate (PMMA) was spin-coated onto the substrate and patterned by electron beam lithography as shown in figure 1(a). After development, the patterned surface was metallized via electron beam physical vapor deposition (PVD) with 3 nm titanium (Ti) for adhesion and 40 nm Au (figure 1(b)). A lift-off process resulted in the nanorods remaining on the substrate (figure 1(c)). As a result, nanorods of 500 nm × 100 nm and 40 nm thick were made with a separation distance of about 500 nm, sufficient to obtain negligible nearest neighbor near-field coupling but finite far-field coupling [71]. This arrangement permits the investigation of both the individual particle’s near-field and the multiple particle effect in far-field. Six matrices of 100 × 100 µm² area separated from each other by 100 µm in both directions, as imaged by dark-field microscopy in figure 1(d), were obtained such that the only difference between each matrix was the orientation of the nanorods, hereafter referred to as ϕ. Both the length and the width of the nanorods, and therefore the aspect ratio (AR), changed between the different series since the process was modified only by changing the electron beam doses from 1.4 up to 2.2 with an increment of 0.4. Thus the sample, as shown in figure 1(d), was composed of three series of six matrices of gold nanorods with different orientations ϕ, and AR ranging from 3.1 to 3.9. Regarding the ϕ = 0° rod orientation as parallel to the incident polarization, the rods are labeled as ϕ = 15°, 45°, 60°, 75°, and 90°. The first matrix was taken as the reference with a 0° orientation and was therefore mounted such that the nanorods’ long axis is positioned parallel to the NSOM illumination polarization. The other matrices are composed of nanorods of the same geometry but angled at ϕ, as shown in the SEM images in figure 1(e) (all the geometric parameters for all the three series (A–C) are charted in figure 5(b)).

We first used a commercial WiTec Alpha NSOM employing a hollow tip microcantilever probe (figures 2 and 3) to study the effect of the excitation polarization on the fabricated arrays of nanorods. The microcantilever-based NSOM rather than a fiber-based system offers superior mechanical (force) sensitivity and optical stability. The output beam of a 532 nm diode laser with maximum power $P_{\text{max}} = 10$ mW was focused onto an aperture (with a less than 100 nm diameter) to deliver a confined light source. The tip–sample distance was regulated by a feedback system based on the optical deflection of a weak 785 nm laser as in contact-mode atomic force microscopy.

Prior to mounting the sample, the arbitrary orientation of the fixed polarization of the NSOM illumination was carefully measured with a linear analyzer. The polarization extinction ratio was determined to have 70% transmission in one phase quadrature and 30% in the other, thus the illumination was not a purely linear source. The sample was then mounted such that the 0° matrix was parallel to the primary polarization of the NSOM. Test scans of the topography were analyzed to ensure the proper mounting angle. In order to carry out measurements from one matrix to another without compromising the optical alignment, a long-range xy-piezostage on the sample plane was used to...
relocate the matrix positions that were identified with visual markers. Each matrix was thus aligned with the NSOM tip by translating the sample from the 0° oriented nanorods to any other series. This is critical to minimize experimental variables and to reduce any possible fluctuations.

Near-field measurements were carried out in transmission mode (figure 2), minimally reconfigured, and then continued in reflection mode (figure 3). The fiber input of the avalanche photodiode (APD) facilitated the commutation from one mode to another. The topographic feedback, the APD output linked to a TTL counting module, and the xy-scanning parameters were controlled and recorded simultaneously. For the transmission measurements in figure 2, the light was collected by an inverted Nikon 60× (0.80 NA, 0.3 WD) microscope objective and was subsequently directed to the APD–photon-counter assembly. For the reflection measurements in figure 3, the scattered light was collected from the top of the sample. The physical size of the objective/probe apparatus limits how the scattered light from the surface can be collected. Thus the collective lens (100 mm FL) was positioned such that its optical axis was nearly parallel to the substrate and was focused on the reflected light directly under the probe tip. The collected light (up to 14° from the plane of the sample surface) was then directed to an optical fiber that was attached to the input of the APD.

Having described the fabrication, positioning and imaging procedures, we now proceed to describe the local spectral measurements using the experimental setup shown in figure 5(a). White light from a tungsten halogen source (HL 2000, Ocean Optics) is focused onto a 50 μm pinhole with a two lens assembly. After the pinhole, the light is collected by a second assembly of two lenses L3 and L4 in figure 5(a) in order to focus the light onto the sample plane positioned at the conjugated plane of the pinhole. This arrangement permits a fairly localized illumination area of only 50 μm diameter on each array. For polarized spectroscopy, this arrangement reserves a collimated region of the incident light, where a linear polarizer can be introduced without modifying the incident beam profile and without engendering any deviations while rotating the polarization. After passing through the sample at normal incidence, the transmitted light is collected with lenses L5 and L6 and coupled to a fiber, which is routed to an optical spectrum analyzer (ANDO AQ 6315A). The sample placement is automated to within 3 μm in the xy-direction allowing translation from one matrix to another, after determining the coordinates of the two extreme matrices. While determining the relative coordinates, we evaluated a 3° deviation between the sample plane and the 0° incident polarization. This was compensated by the linear polarizer’s relative setting in the incident beam path. The incident polarization could thus be consistently varied from 0° to 90° with increments of 10°. This allowed the determination of the polarization dependence of the spectral measurements in the range of 500–1000 nm at a maximum power of 8 nW at the sample plane. A reference measurement was carried out with respect to the substrate response before investigating each series to eliminate any polarization effects not directly associated with the particles. Specifically, the polarization effects of the substrate and the ITO layer are discriminated from the nanorod polarization effects during the transmission mapping. For each incident polarization and for each series a spectrum of the free space (to prevent source fluctuations) and through the substrate + ITO layer (to prevent polarization effects other than those resulting from the nanorods), is recorded. Apart from providing a damping mechanism, the 3 nm Ti adhesive layer mainly shifts the resonances spectrally without disturbing the relative measurements from one matrix to another as this layer is common to all particles. A certain shift of the dispersion relations of the rods is anticipated, which in the case of quartz in the visible part of the spectrum can be reasonably approximated to be small. This situation is fairly well known, for example, in the case of plasmon excitation in a thin metal film where the plasmon dispersion relations can be shown to experience a red shift as a result of the introduction of the quartz medium [72]. For substrates with more complex frequency dependent dielectric functions, the shift is naturally more elaborate. For such studies direct deposition of gold on quartz, that is, without the use of adhesive layers, would be advantageous in interpreting the experimental results. However, we found that for the purposes of our investigations, the use of adhesive layers allowed better precision and consistency in the fabrication process.

3. Results and discussion

We begin the discussion of our results by considering the reflection and transmission mode near-field optical measurements, carried out to study the resonant properties of the nanorods. With reference to figures 2 and 3, we therefore
measure the associated intensity distribution, as a function of the incident polarization relative to the nanorod axis of symmetry. As can be seen, in both configurations, while the excitation is furnished in the near-field, the detection occurs in the far-field. For these nanorod samples, we found that higher incident intensity was required to produce an adequate photon count per second in reflection mode as compared to transmission mode. Thus all the transmission measurements were conducted at 1.84 mW power, while all the reflection measurements were at 8 mW power. Transmission scans over the nanorods ranged from 2200 to 6100 counts s\(^{-1}\); reflection scans over the nanorods ranged from 200 to 700 counts s\(^{-1}\). Transmission scans over an area of plain ITO under the same experimental conditions had a range of 12000 to 15000 photon counts s\(^{-1}\); reflection scans over the ITO ranged from 350 to 450 photon counts s\(^{-1}\). The detection path in transmission mode is encapsulated in a nearly light-tight chamber that minimizes background noise. However, the reflection mode collection uses a somewhat open optics configuration that is more susceptible to noise from stray light sources.

The resulting 1.6 µm × 1.6 µm images for reflection, transmission and simultaneous topography are shown in figure 4. The topographical anomalies and defects are assumed to be due to the fabrication processes. The images clearly show contrast variations in the vicinity of the metallic structures, especially at the edges parallel to the primary polarization. The longitudinal polarization at 0° (row 1 of figure 4) and transverse polarization at 90° (row 2 of figure 4) are displayed adjacently since the difference in the response between the two is greatest. The optical images of orientations 15°, 45°, 60°, and 75° show a progressive conversion from longitudinal to transverse polarization. We note that all reflection and transmission images contain artifacts from the topographic feedback as well. The scattering effects are more strongly pronounced in the transmission images than in the reflection images. This can in part be attributed to the limitations of the experimental setup, where the collected signal in the reflection mode is not as efficient as in transmission (see figures 2 and 3). At the longitudinal polarization, the signal corresponding to the loci of the 40 nm thick nanorods appears to present a degree of transmission that cannot be accounted for by removing possible background counts. However, there is a noticeable drop in the signal occurring along one of the long sides parallel to the polarization. The darkest regions of low photon count (2234–3810 counts s\(^{-1}\)) extend as much as 160 nm away from the topographic edge into the ITO-only region. The other long side exhibits a much smaller region of reduced photon count and could be due to topography effects. A low photon count is due to either (back-) scattered light (which did not get collected by the objective) or excitation of surface modes of the visited nanorod. If the excited mode is radiative, then contribution to the signal may be expected when the mode decays. This process may be compared to the case of a metal film, where plasmons can decay radiatively by virtue of the encountered metal particles, surface roughness, grating, or other symmetry-breaking material geometries allowing for consumption of the excess momentum of the surface plasmons. At the transverse polarization, there are low photon count regions corresponding to the nanorod location and edges parallel to the primary polarization, which in this case happens to be on the short sides. The dark region on the
upper edge of the nanorod image is smaller than that of the lower one. One hypothesis is that the top–bottom differences may be attributable in part to the small mounting angle of the microcantilever probe which could deliver an asymmetric distribution of light, primarily affecting the upper and lower parts of the image of a structure. Another explanation is imperfections in the probe tip geometry. All the images are repeatable over several days at different scan locations with the same probe and sample. Furthermore, the horizontal fast scans in both directions produce approximately equivalent images, both optical and topographical. These near-field measurements evaluate the individual rod response, which, due to preferential polarization, may be interpreted and used to assess the polarization of the source light. Far-field or dark-field spectroscopy cannot be exploited for this method of polarimetry since a collective response has little precision in accessing information on the individual rods.

The reflection images, although less dramatic, showed signs of congruity with the transmission images. Examining the contrast variation on and in between the nanorods, general features similar to the transmission data may be observed. The very low reflectivity of the sample is consistent with the transmission data which revealed the rods and ITO surfaces to be fairly transparent at this wavelength. In the reflection images between the nanorods, a darker region occurs directly above the upper edges of the nanorods, indicating a low photon count. Moreover, directly below the lower edges of the nanorods this dark area does not occur, which can be interpreted as more reflected light. However, since the signal is not particularly high in these regions, one may argue that the low count in the corresponding region of the transmission data is not entirely due to the reflection of light supporting the excitation of the surface modes. These first results suggest the consideration of such series of arrays for polarization diagnostics. Naturally, for any such study, the material, size, shape and geometric arrangement of the structures have to be carefully designed. Realizing that the fabricated structures are not optimum for this purpose, we proceed to explore the far-field spectral response of such series of nanorod arrays as a function of incident polarization and wavelength.

Referring to figure 5, the spectral response in the form of transmission mappings for the A series is presented in figure 6.
Figure 6. Transmission mapping with respect to the incident wavelength and polarization for nanorod orientation (series A) $\varphi = 0^\circ$ in (a), $15^\circ$ in (b), $45^\circ$ in (c), $65^\circ$ in (d), $75^\circ$ in (e), and $90^\circ$ in (f). The inset SEM images show the nanorod orientation of the corresponding array. The indicated values of the contour level are for the measured transmission scaled with the corresponding reference value (that is, with respect to the spectrum of the substrate, inset in figure 5(a)).

as functions of incident wavelength $\lambda$ and polarization state $P$ (measured relative to the substrate response) for each nanorod orientation $\varphi$. The contours in red represent the minimum transmission values. The transmission is clearly orientation and polarization dependent as seen by the localization of the transmission peaks. Moreover, by extrapolations of the loci of the transmission peak values (see figure 7), an inflection point $P_i$ of approximately $45^\circ$ and at a relatively unchanged $\lambda_i$ just below $710$ nm for series A, $705$ nm for B, $695$ nm for C is observed. This provides evidence that for such excitations every orientation for each series (i.e. fixed AR) responds similarly. This is expected as the $45^\circ$ polarization leads to equal excitation of both longitudinal and transverse resonance modes. Above and below this inflection point two regions are observed that depend on $\varphi$. Indeed, for $\varphi$ below $45^\circ$, as in figures 6(a)–(c) and 7 for each series, the transmission peaks occurred in two regions that are ($\lambda < \lambda_i$) associated with ($P < P_i$) or ($\lambda > \lambda_i$) with ($P > P_i$). For $\varphi$ above $45^\circ$, figures 6(d)–(f) and 7 (circle symbols), the peak regions occurred for ($\lambda < \lambda_i$) with ($P > P_i$) or ($\lambda > \lambda_i$) with ($P < P_i$). This is to be expected as stronger resonances will be excited when the $\varphi$ and $P$ are (nearly) equal, as observed in the NSOM measurements. Note also that the resonance wavelength depends on the AR of the nanoparticles, explaining the variation in $\lambda_i$ from one series to another; one can therefore cover a large spectral range allowing polarimetric spectroscopy. Furthermore, the polar plots of figure 7 expose the peak amplitudes for $\varphi = 0^\circ$ and $90^\circ$ as a function of the angle between $\varphi$ and $P$. In the three series, good agreement between both curves is observed. This was targeted to highlight the reciprocal influence of the particle orientations versus the incident polarizations. This is an important observation toward the potential adaptation of such nanostructured arrays for polarimetry.

The potential of the presented study toward polarization measurements is further supported by the computational results presented in figures 8 and 9. The root mean square (RMS) values of the electric field $M(E)$ were computed for two sets of structures employing the finite difference time domain (FDTD) numerical technique. Noting that the computational results are primarily targeted to support the suggested potential application of the nanorods in polarimetry, we proposed the particular nanoscale architecture of parallel rods of varying lengths (for the study of length dependence of the nanorod resonance) as well as circularly arranged rods of fixed lengths for clockwise or counter clockwise visualization of the fields (for the study of orientation dependence). For these structures, the discretized Maxwell equations can be solved directly on a Yee cell in a sufficiently large
Figure 7. Loci of the transmission peak values for each incident polarization $P$ and particle orientation $\varphi$. The $\varphi$ are distinguished by the symbols in the graphs. The transmission peak wavelength and amplitude are represented in the first and second column respectively. The peak amplitude is plotted for $\varphi = 0^\circ$ and $90^\circ$, as a function of the relative angle $\theta$ (between $\varphi$ and $P$). Part (a) is for the case of series A, (b) for series B and (c) for series C. The black arrow underlines the inflection point occurring at $P = 45^\circ$ specific to each AR.

computational domain. The domain, incorporating uniaxial perfectly matched layer absorbing boundary conditions, can be excited with a linearly polarized field. The simulations were carried out in the harmonic mode at a wavelength of 655 nm. The dielectric function of gold was embedded numerically by an analytical fitting using an extended Drude function (see for example Vial et al [73] on gold dispersion for application to the modeling of extinction spectra within the FDTD). The AR effect is illustrated in the left columns of figures 8 and 9 for AR ranging from 1 to 5 showing pronounced resonances depending on the excitation parameters and the AR matching. In the right columns of figures 8 and 9, the AR is fixed at 3, close to the experimental conditions, and the incident polarization is taken to be horizontal (along the structures with $\varphi = 0^\circ$). The resulting near-field distributions $M(E_i, i = x, y, z)$, show strong disparities from one $\varphi$ to another. From $0^\circ$ to $90^\circ$, the near-field distribution goes from the edges of the structures to the long sides of the structures, respectively. For intermediate $\varphi$, the field is distributed along the sides and is more pronounced at one edge (pointing toward the horizontal axis, that is, the incident $P$ direction). The results suggest that such devices can be proposed for polarimetry and/or beam diagnostics. We note that a potential use of the proposed nanorods toward the determination of the polarization state of an incident beam would initially be based on a mapping of the field distribution of a device similar to or more elaborate than what is shown in figures 8 and 9. Thus, the traditional extinction ratio, i.e., the ratio of the transmitted (passed polarization state) to the orthogonal (attenuated) polarization state, which is an important figure of merit for polarization sensitive devices such as the segmented wire grid polarizers used in polarimetry, will require a revision for the proposed nanopolarimetry. Therefore, while the results demonstrate that
Figure 8. Computed RMS modulus ($M$) of the surface electric field distribution as a function of nanorods’ aspect ratio (left) and orientation (right). The excitation polarization was selected along the parallel rods, that is, in the $x$-direction. The total FDTD simulation time was 5 periods at a wavelength of 655 nm in a harmonic mode. The potential for nanopolarimetry using angularly organized rods can be investigated by their fields, as visualized with the distribution of the three orthogonal field components.

Figure 9. Cross sectional visualization of the distribution of the maximum near-field RMS modulus sustained by the gold nanorods. AR dependent field oscillation and size and orientation dependent field enhancement (when compared to the background field) are clearly discernible. The nanorods (dimensions $L_x$, $L_y$, $L_z$) are semi-transparently shown in blue. All other parameters are identical to those of figure 8.

The nanorods probe the linear states of polarization, the initial measurements do not fully support the idea that they perform any polarimetric function, such as scattering particular states of polarization that can be quantified in a measurement. In future studies, stronger evidence could be acquired by augmenting the experiments with the ability to control the
Figure 10. Comparison between ordered nanorods and random islands. (a) Spectra obtained for circular light from nanorods oriented at 0° and 90°. (b) Spectra obtained for the two incident crossed polarizations on annealed and unannealed (random) islands. In both cases, the trends are similar whether the randomness concerns the incident light polarization or the nanoparticles’ size distribution and orientations. The arrows in the SEM images show the considered polarizations, and the color code links the plotted curves to the defined orientation (a) or polarization (b).

Figure 11. Example of a potential nanopolarimeter implementation. In (a), a Bayer filter representation is given as a comparison with the exposed nanopolarimeter concept in (b), where one pixel would result from the analysis of different orientations to potentially access the incident polarization state.

phase retardance allowing the measurements to be extended to the Poincaré sphere.

Finally, in figure 10, we compare excitation with circular polarization of ordered nanoparticles versus linear polarization of nanoparticles with random size distribution and orientations. In figure 10(a), we display the spectra for incident circular polarization. The associated SEM images highlight the orientation of the nanorod arrays with respect to the circular polarization. No orientation effects are observed when the incident polarization is circular, indicating that the same resonances are excited. In the case of random nanostructures (here annealed and unannealed nano-islands), we used well-defined incident polarizations of 0° (i.e. horizontal) and 90° (i.e. vertical) as illustrated in the SEM images of figure 10(b). Similarly to the case of figure 10(a), no polarization influence is highlighted when the nano-islands’ sizes and orientations are random. This confirms that the random criterion can either come from nano-object geometric features ϕ or the incident polarization P. The above analysis implies that ordered nanoparticle arrays may be used for spectroscopic polarimetry using both the AR (to cover a large spectral range) and the orientation of the particles (to study the polarization state). For example, one may envisage the fabrication of an array of alternating series of orientations, as in a Bayer filter for color imaging, but where the pixel would be described by several orientations, as illustrated in figure 11. Such a system could diagnose the polarization state of an incident beam.

4. Conclusion

Plasmon excitation and optical resonances in metal nanorods produce strong field enhancement and confinement, and as a result any nanorod decorated substrate would be affected in its reflection, transmission, and absorption properties. Specially
designed nanostructures, in the form of gold nanorods with various relative rotational positions fabricated on a transparent substrate were shown to permit the study of polarization effects using a fixed polarized light source, thus lifting the experimental burden of modifying the light source orientation mechanically. The far-field reflection and transmission images in response to near-field excitation revealed polarization dependent local field intensity variations in the vicinity of the nanorods. The transmission images showed remarkable differences between the longitudinal and transverse cases. This confirms the anisotropy of the nanorod symmetry axis that is the origin of the orientation dependent response. The near-field studies in conjunction with the topographic information presented show the overall scattering properties of the fabricated nanostructures. While the single wavelength absorption properties, in the case of near-field excitations, are seen to clearly be a function of the polarization state of the interacting electromagnetic field, the results in the case of collective spectral measurements reveal that the near-field illumination wavelength falls below the main absorption band of the structures. One may readily conclude from the presented contour plots that not only does this rather broad (≈200 nm) spectral band exhibit a polarization dependent shift, but it also clearly reveals an orientation dependence. While further spectroscopic near-field imaging is warranted to fully map the effect of the absorption properties of the nanorods on the transmission and reflection images, the single wavelength, single polarization images presented clearly differentiate the various orientations. Supported by computational visualization of the near fields, the presented results show that the polarimetric response of nanorod arrays of different ARs as a function of both the incident polarization and the nanorod orientations may be assessed. For cases where $\psi$ and $P$ are fixed with respect to each other, the results suggest the potential for polarimetry measurements depending on the intended application, that is, either for incident light diagnostics or for polarization state determination of an object (i.e. polarimetry imaging as in a pixelated polarizer imaging polarimeter, as illustrated in figure 11). For the purposes of this work, the results suggest a potential approach to overcoming the challenge of using arrays of antennas coupled to a detector structure such that it selects out a single linear or circular polarization component of the field. The studied system is promising for the development of integrated optical components for numerous polarization-based techniques such as integrated birefringent systems [74], liquid crystal displays, or microscopy techniques [68].

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