Highly tunable plasmonic nanoring arrays for nanoparticle manipulation and detection

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Abstract
The advancement of trapping and detection of nano-objects at very low laser powers in the near-infra-red region (NIR) is crucial for many applications. Singular visible-light nano-optics based on abrupt phase changes have recently demonstrated a significant improvement in molecule detection. Here, we propose and demonstrate tunable plasmonic nanodevices, which can improve both the trapping field enhancement and detection of nano-objects using singular phase drops in the NIR range. The plasmonic nanostructures, which consist of gaps with dimensions 50 nm × 50 nm connecting nanorings in arrays is discussed. These gaps act as individual detection and trapping sites. The tunability of the system is evident from extinction and reflection spectra while increasing the aperture size in the arrays. Additionally, in the region where the plasmonic nano-array exhibits topologically-protected, near-zero reflection behaviour, the phase displays a rapid change. Our experimental data predict that, using this abrupt phase changes, one can improve the detection sensitivity by 10 times compared to the extinction spectra method. We finally report experimental evidence of 100 nm polystyrene beads trapping using low incident power on these devices. The overall design demonstrates strong capability as an optical, label-free, non-destructive tool for single molecule manipulation where low trapping intensity, minimal photo bleaching and high sensitivity is required.

Keywords: nanofabrication, nanoplasmonic arrays, ellipsometry, sensing, nanoparticle trapping

(Some figures may appear in colour only in the online journal)

1. Introduction
Since the early realisations of optical confinement of microparticles [1, 2], the field of optical manipulation has evolved beyond simple trapping to encompass more complex operations involving the control of individual particles. The need for the manipulation of nanoscale and biological objects was apparent during the early stages of development of these techniques [3]. Nanoscale confinement is of particular importance in the territory of nanophotonics since its implementation may lead to the precise control of biological samples. This degree of control is necessary to study in detail the structures of such nanoscale objects and their interactions with other systems. Using the standard optical tweezers technique, direct optical manipulation is restricted to moderately larger systems such as cells [4], bacteria [5] and DNA strains [6]. In recent years, different approaches have been studied to overcome this size limitation, such as slotted waveguides [7], plasmonic structures [8, 9] and photonic crystal cavities [10]. Plasmonic devices have received special attention due to their ability to confine nanoparticles [11–13], and their potential applications in the field of surface-enhanced spectroscopy [14–18]. It has been shown that plasmonic devices can be used to trap and detect silica nanoparticles as small as 12 nm [19] or single proteins [13] using low laser powers through the self-induced back action (SIBA) mechanism [20]. It has been shown that, by carefully manipulating the phase of light, one can create ‘twisted’ photons [21, 22] and
In order to enhance the detection ability of tools based on plasmonic devices one can take advantage of the rapid phase changes that occur for certain plasmonic geometries. The phase of light can exhibit peculiar behaviour; for example, its value becomes ill-defined at the central singularity of helical beams with non-zero orbital angular momentum. The peculiarity of the phase of light has led to many interesting phenomena such as the Aharonov–Bohm effect and the Berry phase of quantum systems. It is also known that topological effects, i.e. extremely narrow plasmonic resonances that manifest at low light intensity regions, can be used to our advantage in order to enhance sensitivity. Dark regions of ‘light’ can be created using various methods such as multiple beam interference, higher order beams and near-fields. It has been demonstrated that plasmonic metamaterials can induce rapid phase changes to achieve greater sensitivity and, hence, detect biomolecules in the visible spectrum. Additionally, these devices exhibit topological effects such as the Berry phase of quantum systems and the Aharonov–Bohm effect, which could also be used for optical manipulation and sorting of nanoscale matter or refractive index sensing, depending on the method of plasmonic excitation.

2. Methods

We used electron beam lithography (EBL) to fabricate the devices. Figures 1(a) and (b) show scanning electron microscopy (SEM) images of the resulting devices, with outer ring diameters of 300 nm and an inner disk diameter, $d$, which varies from device to device. The connecting slits are 50 nm, both in width and length, and the array pitch is 350 nm. The plasmonic structures are fabricated on commercially-available quartz substrates, which are initially coated with an indium tin oxide (ITO) coating to provide a conductive layer. A 150 nm layer of SX AR-P6200 photoresist is spin-coated onto the ITO layer. The array design is transferred to the coated glass substrate via EBL (Elionix ELS-7500EX) with the probe current and acceleration voltage set to 10 pA and 50 kV, respectively. The fabricated structures are covered by a thin titanium layer, which aids the adhesion of gold. A 50 nm layer of gold is deposited via electron beam vapour deposition (Kawasaki KE604TT1-TKF1). Finally, the lift-off process takes place where the excess photoresist along with the metal layers are removed. The same devices were imaged while tilted by 35° (figures 1(c) and (d)) in order to show imperfections that arise during fabrication. The tilted SEM images show the smoothed edges in the features of the devices caused by charging effects. As a consequence, the nanostructured sidewalls were slanted with angles of ∼20°. The dimensions of metamaterials by measuring the phase angle of polarization properties of light upon re-polarisation.



\[ \text{Photoresist} \times 50 \text{ nm}. \]

\[
\begin{align*}
\text{Inner disk diameter, } d, \text{ is varied as (a) no disk and (b) 150 nm; (c) and (d) SEM images with the same } d \text{ as in (a) and (b) when the sample is tilted by 35°. (e) The devices are illuminated with a white light source after fabrication. The change in the transmitted colours for different values of } d \text{ suggests that the shift in transmission is due to the varying inner disk diameter. (f) Schematic of the hybrid structure.}
\end{align*}
\]

Figure 1. (a)-(d) SEM images of fabricated devices. The outer ring diameter for all the shown devices is 300 nm and the connecting slit has a dimension of 50 nm × 50 nm. The inner disk diameter, $d$, is varied as (a) no disk and (b) 150 nm; (c) and (d) SEM images with the same $d$ as in (a) and (b) when the sample is tilted by 35°. (e) The devices are illuminated with a white light source after fabrication. The change in the transmitted colours for different values of $d$ suggests that the shift in transmission is due to the varying inner disk diameter. (f) Schematic of the hybrid structure.
of the various features of the fabricated devices may also differ by a few nanometres from the designed values.

The devices are first monitored under an optical microscope and illuminated by a white light source. The first evidence of the tunability of the devices comes from the transmitted colour, which exhibits a shift for different gold disk diameters as shown in figure 1(e). This colour change is due to the splitting of the resonance modes as a result of the hybrid nanostructured plasmonic design [34, 35]. One of the obtained resonances is the cylindrical surface plasmon (CSP) resonance located in the VIS spectrum range, leading to the observed colour change. The fabricated devices are then used to obtain extinction and reflection spectra using a microspectrophotometer system (CRAIC 20/30 PV). The ellipsometric parameters are measured using a Horiba UNISEL 2 ellipsometer. All the extinction, reflection and ellipsometric spectra are measured for different linear polarisation orientations, i.e. longitudinal and transverse with respect to the trapping gap axis (figure 1(f)).

3. Results and discussion

3.1. Theoretical simulation and experiment of the extinction and reflection spectroscopy

Figures 2(a) and (b) show the extinction, reflection and the ellipsometric spectroscopic measurements obtained for \( d = 150 \) nm. The configuration where the light is polarised perpendicular to the gap exhibited more pronounced features compared to the longitudinal orientation within the studied wavelength region. In the case of the extinction spectra, we observed two individual peaks, one residing in the VIS spectrum range and one in the NIR while in the transverse orientation. The same spectra for the opposite orientation showed only the first peak. Similar behaviour was observed for the reflection spectra. The presence of the extinction peak around 950 nm for the transverse orientation can be explained by a simple dipole–dipole model that describes the system when the nano-objects approach each other [40, 41]. In the ellipsometric spectra the observed drop of the angle, \( \Psi \), for the case where the devices were rotated by \( \varphi = 90^\circ \) (figure 2(c)) was more dramatic than for the orthogonal orientation. Previous work on gold nanoring dimers also showed that the polarisation configurations perpendicular to the ring structures show more substantial shifting of the extinction peaks towards the infra-red [33]. Considering these results the rest of the theoretical and experimental data were acquired selecting transverse linearly polarised light.

With the intention of demonstrating the tunability of this design, we first carried out finite difference time domain simulations. Figure 3 shows the theoretically and experimentally obtained values for the extinction and reflection spectra for various inner disk diameters, \( d \), for the cases where the sample was immersed both in air and water. The spectra reveal a red-shift for both extinction peaks as well as the reflection dips when the surrounding medium changes from air to water. In figure 3(a), noteworthy point is that the theoretical extinction curves, which were performed in air, show two major peaks: the first one residing in the VIS and the second in the NIR region. These peaks come from two resonances that are excited in the device and strongly depend on the structure’s geometry. The first peak resonance in the 540–574 nm region is a result of a Fabry–Pérot-like (FP) resonator. These resonance peaks originate from the charge distribution that is accumulated in the space between the inner disk and the outer ring. These polaritons are reflected at the boundaries of these two features, thus creating a FP resonance in the aperture [42–44]. In both our theoretical and experimental results, we observed that the foretold peak exhibits a shift towards the infra-red, which is in agreement with previous theoretical work that demonstrated an increase in
transmission of the CSP resonance for larger wavelengths with increasing $d$ or equally decreasing aperture size [45]. This resonance was not so obvious for smaller $d$ values, i.e. 0 and 50 nm, due to the absence or the small size of the inner disk. Instead, an extinction maximum is observed around 530 nm; this is also present for all $d$ values. This peak is associated with a ring only geometry [46]. For $d = 100$ nm this peak and the CSP peak seem to partially overlap. The second peak, $P$, around 860–910 nm that appears in the results comes from what is referred to as the plasmonic resonance [42, 47]. In this case, the charges are accumulated at the sharp edges of the 50 nm gap (dashed circle figure 1(f)). This dipole-like charge distribution determines the strength of the field enhancement in these gap areas. As $d$ increases from 0–200 nm the electric field distribution, extinction and reflection peak positions are also modified. It is our belief that the red shifting of this NIR plasmonic resonance is due to the coupling between the CSP and the $P$ oscillator modes. In previous theoretical and experimental works considering ring-near-disk cavities, similar behaviour was observed while the separation between cavities was decreased [48]. In our devices, as the gap between the inner disk and outer ring surface becomes smaller, the interaction between the disk and ring modes becomes stronger. This results in an increased interference between the CSP and $P$ mode resonators, leading to the observed red-shift of the plasmonic $P$ resonance. It is apparent that theoretically and experimentally obtained values are in reasonable agreement. Any discrepancies between the two are mainly due to imperfections during the fabrication of the samples, such as charging effects. These effects cause the edges of the features in the structure to be rounded in reality, whereas in simulations they are considered to be sharp (figures 1(c) and (d)) [49].

The same spectra were compared when the device was surrounded by water, since, in optical manipulation experiments, samples are often immersed in aqueous solutions. The
same overall trend in behaviour was observed in the two media; however, in water, the overall spectral shift is larger. As a result, this device design could be used to detect changes in refractive index.

In detail, we observed shifting of the CSP resonance up to 75 nm when comparing the two surrounding media and a maximum of 175 nm for the plasmonic peak, P. The shift of the resonance peaks increases as \( d \) increases with the \( d = 200 \text{ nm} \) case contributing to the largest shift (175 nm), while for \( d = 0 \text{ nm} \) the shift was found to be 160 nm. Figure 4 shows the wavelength shift per refractive index unit (RIU) of the CSP and plasmonic resonances as a function of \( d \). For the case of the CSP resonance, the inner disk diameters of 0 and 50 nm were omitted from the data since the red shift was not obvious for these values. Our theoretical calculations show larger shifts per RIU for larger \( d \) values for both peaks. Specifically, the plasmonic peak exhibits a peak displacement of 485 nm/RIU (theory) and 250 nm/RIU (experiment) when \( d = 0 \text{ nm} \), while \( d = 200 \text{ nm} \) shows 526 nm/RIU (theory) and 305 nm/RIU (experiment). For the CSP resonance, the maximum shift was again associated with the largest inner disk diameter and was found to be 230 nm/RIU (theory) and 85 nm/RIU (experiment). Even though theory and experiment show some discrepancy in terms of the wavelength shift values, it is still apparent that larger \( d \) offers better refractive index sensitivity. The differences between theory and experiments can be again attributed to fabrication imperfections as discussed previously.

### 3.2. Tunable singular phase drop in plasmonic nanoring arrays

In this section, we considered a different approach to improve the sensitivity of the devices. It has been shown that, by using the phase of light under surface plasmon resonance conditions, one can enhance the sensitivity of plasmonic nanostructured arrays for refractive index changes [50] and even detect single nanoparticles/molecules [28]. Due to the fact that the phase is not defined when the light intensity is zero, it can show rapid changes as the light intensity approaches low values. This effect can be used to detect nano-objects attached to structures in which these changes manifest. The devices used in our work exhibit such phase behaviour at certain wavelengths depending on the inner ring diameter. Ellipsometric spectra of the fabricated devices were collected with the aid of a spectroscopic ellipsometer, which measures the ratio between the p-polarised, \( r_p \), and s-polarised, \( r_s \), components of the reflected light such that

\[
\frac{r_p}{r_s} = \tan(\Psi)e^{i\Delta},
\]

where \( \Psi \) and \( \Delta \) are ellipsometric angles, which define the amplitude ratio and phase difference, respectively.

To evaluate the point of low light intensity, \( \Psi \) was measured for different inner ring diameters for varying incidence light angles. Figures 5(a) and (b) show the obtained \( \Psi \) values with respect to the incident wavelength for \( d = 0 \text{ nm} \) and \( d = 150 \text{ nm} \), respectively. It is evident that \( \Psi \) decreases at some point for each device and this point implies a light intensity minimum. It is also apparent that this point of low light intensity is red-shifted as the inner ring diameter is increased, with the larger diameters displaying their minima in the NIR thus confirming the high tunability of this design. The phase angle, \( \Delta \), was acquired for the same devices. Figures 5(c) and (d) present the phase difference for the same wavelength range and identical inner disk diameters as in figures 5(a) and (b). As expected, \( \Delta \) shows a change in the same region where the drop in \( \Psi \) was observed. Figure 5(e) shows where these abrupt phase changes occur for each inner disk diameter considered in our studies. The fact that phase exhibits such a degree of change, which can be tuned by modifying \( d \), suggests that this design can be used for highly sensitive particle detection. As we approach this condition of
darkness, i.e. a large drop in $\Psi$, the phase sensitivity of the system increases [26, 50]. This condition is highly dependent on the incident angle, $\theta_{\text{inc}}$, and the geometry of the system [28].

Figure 5 illustrates the influence of the incident angle on the ellipsometric spectra. It is obvious that, as the incident angle increases, a slight shift in the associated wavelength is observed. In addition to this shift, the changes in both $\Psi$ and $\Delta$ seem to be more pronounced for some angles than others. In particular, we have found that the maximum change in $\Delta$ ($32^\circ$) was observed when $d = 150$ nm and $\theta_{\text{inc}} = 67^\circ$ and the smallest change ($13^\circ$) occurs for $d = 0$ nm and $\theta_{\text{inc}} = 60^\circ$.

**Figure 5.** Ellipsometric angles, $\Psi$ (a)–(b) and $\Delta$ (c)–(d), for different inner disk diameters and varying incident angle from $60^\circ$–$70^\circ$. The inner disk diameter is $d = 0$ nm (a)–(c) and 150 nm (b)–(d). The minimum in each plot denotes the point of minimum light intensity for each device parameter. The peak position for all the different parameters are shown in (c). Ellipsometric parameters, $\Psi$ (dashed curves) and $\Delta$ (solid curves), are shown in (f) for an inner disk $d = 150$ nm and incident angle $67^\circ$. The red curves are for air as the surrounding material while the blue curves are based on an assumed refractive index of the surrounding material of $n = 1.02$, corresponding to a 10 nm shift of the extinction peak position.
The sensitivity of the ‘air’ localised plasmon resonance $P$ peaks (figure 3) are of the order of 1 nm per $10^{-3}$ RIU, allowing one to detect the change of the local environment around the connecting nanogap regions with high sensitivity. This observation is comparable to previous reports and, in principle, a detection limit of $10^{-5}$–$10^{-6}$ RIU can be achieved with external amplification/detection techniques $[50, 51]$. In order to improve the sensitivity of the devices we considered the parameters for which we observed the maximum change in phase and assumed an increase in the refractive index of the surrounding material, $dn$, to be of the order of 0.02 (corresponding to a 10 nm extinction peak shift). The calculations shown in figure 5(f) led to a phase change of $15^\circ$, which is ten times greater than the change in $\Psi$ which was only $\sim 1.5^\circ$. Assuming a phase noise level of the ellipsometer of $0.5^\circ$, we can finally evaluate the sensitivity of the suggested plasmonic nanostructures to local refractive index changes to be approximately $10^{-6}$–$10^{-7}$ RIU. In order to detect such a small change in refractive index by the extinction spectra method discussed previously, one would need to detect wavelengths shifts of less than 0.4 nm. This proves that using the ellipsometric parameters for sensing refractive index changes yields more useable information than if we relied solely on transmission or reflection spectra.

3.3. Demonstration of nanoparticle trapping

We finally investigated the possibility of nanoparticle trapping, which can potentially extend to the study of individual particle dynamics within large particle ensembles, with the use of the transmission, reflection and singular phase drop methods. Figure 6(a) shows the electric field intensity normalised to the incident field for the axes perpendicular to the trapping gap (solid line in the inset) and perpendicular to one of the two inner discs (dashed line). Figure 6(b) summarises these results showing the maximum electric field intensity values for both cases. These calculations were carried out for the configuration where the surrounding medium was water and the incident angle of the light beam was fixed at $\theta_{\text{inc}} = 63^\circ$ to match the experimental conditions. From both figures we predict that the maximum field intensity in the trapping gap area and at the boundaries of the inner discs is observed when $d = 150$ nm. We can also see that, when $d$ approaches the size of the outer ring, i.e. $d = 200$ nm, the
electric field intensity begins to drop in both of the locations studied. Furthermore, simulations for varying incident angles showed that the wavelength position of the plasmonic resonance peak does not significantly change (<10 nm) although multipolar resonances arise in the VIS and NIR regions when the incidence is varied from normal to parallel [49].

We used these predictions to experimentally demonstrate that the design is appropriate for optical trapping of nanoscale particles and to verify our theoretical calculations. We fabricated a single device containing arrays of different inner ring diameter dimensions. This device was excited via the Kretschmann configuration (figure 6(c)), whereby a glass prism is used to generate evanescent fields penetrating into the surrounding medium by total internal reflection. This configuration is commonly used for exciting plasmonic resonances. The glass substrate containing the fabricated structures was placed on the top surface of the prism. To ensure that there was no refractive index difference at the prism-to-glass substrate interface due to air, refractive index matching oil was sandwiched between them. A dense water solution (1:1000) of 100 nm polystyrene beads was prepared and placed on top of the plasmonic structure. A Ti: Sapphire laser was used and the incident power at the edge of the prism was measured to be 1 mW. The incoming beam was aligned to be incident at an angle \( \theta_{inc} = 63° \), and the weakly focused beam addressed all the arrays simultaneously. This incident angle was chosen in order to be close to the critical angle between glass and water \( \theta_{crit} = 61.8° \), thus ensuring optimum evanescent field penetration. Figure 6(d) shows the device as viewed by an optical microscope equipped with a 20X objective with the beam turned off (left) and on (right). We observed that the polystyrene beads were rapidly confined within the arrays, with a greater number of particles trapped at the 150 nm region when compared to the rest. This finding is in agreement with our calculations, proving that for \( d = 150 \) nm maximum trapping fields are achieved.

Additionally, the experimental results indicate enhanced particle trapping performance for \( d = 200 \) nm compared to \( d = 0 \) nm, although the enhancement of the calculated local field intensity at the trapping gaps for the 0 and 200 nm inner disk diameters are very close to each other. In this case, the localised resonances associated with CSPs need to be considered over the entire plasmonic array. As we show in figure 3, the enhanced CSP resonances with increasing size of the inner disk cavities also leads to the red-shift of the reflection dips toward the NIR region. We note that (i) the chosen trapping laser wavelength, \( \lambda = 950 \) nm, is near the minimum reflection region for inner disk diameters in the range of 150–200 nm (see figure 3 for water medium); (ii) the trapping particle diameter (≈100 nm) is comparable to the aperture sizes between the inner disk and the outer ring; (iii) the incident laser powers are very low at less than 1 mW for a low numerical aperture (0.4 NA). These experimental conditions are very similar to the SIBA trapping effects as described in [13, 20, 52]. In this mechanism, instead of considering the trapped particles to be confined at a fixed trap depth, where the particle is nominally high-intensity seeking at the trapping gaps, we can investigate the coupling of the particle’s motion to the oscillator modes between the nanodisk/ring cavities. As a result, the particle can also effectively be trapped in a dynamic intensity minimum at the nanodisk/ring apertures. In brief, the experimental outcome demonstrates the capability of the devices to optically manipulate large nano-object ensembles with low incident powers while tuned to a NIR wavelength.

4. Conclusion

In conclusion, we have presented a hybrid plasmonic design that clearly exhibits high tunability towards the NIR by varying the inner disk diameter; the device is also able to achieve nanoparticle confinement. Additionally, the devices show great potential in refractive index and trapped nano-object detection due to the high sensitivity they provide from the acquisition of extinction, reflection and especially ellipsometric spectra. Theoretical calculations verify our experimental observations. Both simulation and experimental results provide evidence that this device is an excellent tool for optical, label-free, non-destructive manipulation of biological samples. For future work, we suggest using these devices for biomatter manipulation. Additionally, one can use multiple trapping beams and, by rapidly modifying their relative phases, create interference patterns that will allow the transportation of nano-objects along the arrays.

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References

[1] Ashkin A 1970 Acceleration and trapping of particles by radiation Press. Rev. Lett. 24 156
[2] Ashkin A, Dziedzic J M, Bjorkholm J E and Chu S 1986 Observation of a single-beam gradient force optical trap for dielectric particles Opt. Lett. 11 288
[3] Ashkin A, Dziedzic J M and Yaman T 1987 Optical trapping and manipulation of single cells using infrared laser beams Nature 330 769
[4] Liu Y, Sonek G J, Berns M W and Tromberg B J 1996 Physiological monitoring of optically trapped cells: assessing the effects of confinement by 1064 nm laser tweezers using microfluorometry Biophys. J. 71 2158
[5] Ashkin A and Dziedzic J M 1987 Optical trapping and manipulation of viruses and bacteria Science 235 1517
[6] Yang A H J, Moore S D, Schmidt B S, Klug M, Lipson M and Erickson D 2009 Optical manipulation of nanoparticles and biomolecules in sub-wavelength slot waveguides Nature 457 71
[7] Daly M, Truong V G and Nic Chormaic S 2016 Evanscent optical trapping of nanoscale particles using slotted tapered optical fibres Opt. Exp. 24 263072
[8] Sergides M, Truong V G, Pram M, Schloss J R, Bhawardy B S and Nic Chormaic S 2015 Characterization of periodic plasmonic nanoring devices for nanomanipulation Proc. SPIE 9548 95481T
[9] Daly M, Sergides M and Nic Chormaic S 2015 Optical trapping and manipulation of micrometer and submicrometer particles Laser Photonics Rev. 9 309
[10] Song B S, Noda S, Asano T and Akahane Y 2005 Ultra-high-Q photonic double-heterostructure nanocavity Nat. Mater. 4 207

[11] Quidant R and Girard C 2008 Surface-plasmon-based optical manipulation Laser Photonics Rev. 2 47
[12] Juan M L, Righini M and Quidant R 2011 Plasmon nano-optical tweezers Nat. Photon. 5 349

[13] Pang Y and Gordon R 2011 Optical trapping of a single protein Nano Lett. 12 402
[14] Nie S and Emory S R 1997 Probing single molecules and single nanoparticles by surface-enhanced Raman scattering Science 275 1102

[15] Gopinath A, Boriskina S V, Presmari S W, Ziegler L, Reinhard B M and Negro L D 2009 Plasmonic nanogalaxies: multiscale aperiodic arrays for surface-enhanced Raman sensing Nano Lett. 9 3922

[16] Theiss J, Pavaskar P, Echtner M P, Muller R E and Cronin S B 2010 Plasmonic nanoparticle arrays with nanometer separation for high-performance SERS substrates Nano Lett. 10 2749

[17] Tripathy S, Marty R, Lin V K, Teo S L, Ye E, Arbouet A, Sawiot L, Girard C, Han M Y and Mayah A 2011 Acousto-plasmonic and surface-enhanced Raman scattering properties of coupled gold nanospheres/nanodisk trimers Nano Lett. 11 431

[18] Ahmed A and Gordon R 2011 Directivity enhanced Raman spectroscopy using nanoantennas Nano Lett. 11 1800

[19] Pang Y and Gordon R 2011 Optical trapping of 12 nm dielectric spheres using double-nanoholes in a gold film Nano Lett. 11 3763

[20] Juan M J, Gordon R, Pang Y, Eltekhari F and Quidant R 2009 Self-induced back-action optical trapping of dielectric nanoparticles Nat. Phys. 5 915

[21] Allen L, Padgett M J, Babiker M and Wolf E 1999 The orbital angular momentum of light Prog. Opt. 39 291

[22] Molina-Torres G, Torner J P and Torner L 2007 Twisted photons Nat. Phys. 3 305

[23] Nye J and Berry M 1974 Dislocations in wave trains Proc. R. Soc. A 366 155

[24] Aharonov Y and Bohm D 1959 Significance of electromagnetic potentials in the quantum theory Phys. Rev. 115 485

[25] Berry M V 1984 Quantal phase factors accompanying adiabatic changes Proc. R. Soc. A 392 45

[26] Kravets V G, Schedin F and Grigorenko A N 2008 Extremely narrow plasmon resonances based on diffraction coupling of localized plasmons in arrays of metallic nanoparticles Phys. Rev. Lett. 101 087403

[27] Kabashin A K, Patkowsky S and Grigorenko A N 2009 Phase and amplitude sensitivities in surface plasmon resonance bio and chemical sensing Opt. Express 17 21191

[28] Kravets V G et al 2013 Singular phase nano-optics in plasmonic metamaterials for label-free single-molecule detection Nat. Mater. 12 304

[29] Dennis M R, King R P, Jack B, O’Holleran K and Padgett M J 2010 Isolated optical vortex knots Nat. Phys. 6 118

[30] Allen L, Beijersbergen M W, Spreew R J and Woerdman J P 1992 Orbital angular momentum of light and the transformation of Laguerre–Gaussian laser modes Phys. Rev. A 45 8185

[31] Yu N, Genevet P, Kats M A, Aieta F, Tetienne J, Capasso F and Gaburro Z 2011 Light propagation with phase discontinuities: generalized laws of reflection and refraction Science 334 386

[32] Giunzberg P et al 2013 Manipulating polarization of light with ultrathin epsilon-near-zero metamaterials Opt. Express 21 14907

[33] Tsai C Y, Lin J W, Wu C Y, Lin P T, Lu T W and Lee P T 2012 Plasmonic coupling in gold nanoring dimers: observation of coupled bonding mode Nano Lett. 12 1648

[34] Baida F I and van Labeke D 2003 Three-dimensional structures for enhanced transmission through a metallic film: annular aperture arrays Phys. Rev. B 67 155314

[35] Liu Y J, Si G Y, Leong E S P, Xiang N, Danner A J and Teng J H 2012 Light-driven plasmonic color filters by overlaying photosensitive liquid crystals on gold annular aperture arrays Adv. Mater. 24 131

[36] Wen F, Zhang Y, Gotthime S, King N S, Zhang Y, Nordlander P and Halas N J 2015 Charge transfer plasmons: 2D1102 frequency conductances and tunable infrared resonances ACS Nano 9 6428

[37] Prodan E, Radloff C, Halas N J and Nordlander P A 2003 Hybridization model for the plasmon response of complex nanostructures Science 302 419

[38] Aizpurua J, Hanarp P, Sutherland D S, Käll S, Bryant G W and García de Abajo F J 2003 Optical properties of gold nanorings Phys. Rev. Lett. 90 057401

[39] Genet C and Ebbesen T W 2007 Light in tiny holes Nature 445 39

[40] Jain P K, Eustis S and El-Sayed M A 2006 Plasmon coupling in nanorod assemblies: optical absorption, discrete dipole approximation simulation, and exciton-coupling model J. Phys. Chem. B 110 18243

[41] Jain P K, Huang W and El-Sayed M A 2007 On the universal scaling behavior of the distance decay of plasmon coupling in metal nanoparticle pairs: a plasmon ruler equation Nano Lett. 7 2080

[42] Hongcang G, Meyrath P T, Zentgraf T, Liu N, Fu L, Schweizer H and Giessen H 2008 Optical resonances of bowtie slot antennas and their geometry and material dependence Opt. Express 16 7756

[43] De Waele R, Burgos S P, Polman A and Atwater H A 2009 Plasmon dispersion in coaxial waveguides from single-cavity optical transmission measurements Nano Lett. 9 2832

[44] Heshmat B, Li D, Darcie T E and Gordon R 2011 Tuning plasmonic resonances of an annular aperture in metal plate Opt. Express 19 5912

[45] Haftel M I, Schluckermann C and Blumberg G 2006 Enhanced transmission with coaxial nanoparotopes: role of cylindrical surface plasmons Phys. Rev. B 74 235405

[46] Sonnenauf Y, Verellen N, Sobhani H, Vandenbosch G A E, Moshchalkov V V, Van Dorpe P, Nordlander P and Maier S A 2010 Experimental realization of subradiant, superradiant, and Fano resonances in ring/disk plasmonic nanocavities ACS Nano 4 1664

[47] Berthelot J, Acimovic S S, Juan M L, Kreuzer M P, Renger J and Quidant R 2014 Three-dimensional manipulation with scanning near-field optical nanotweezers Nat. Nano 9 295

[48] Verellen N, Sonnenauf Y, Sobhani H, Hao F, Moshchalkov V V, Van Dorpe P, Nordlander P and Maier S A 2009 Fano resonances in individual coherent plasmonic nanocavities Nano Lett. 9 1663

[49] Hao F, Larsson E M, Ali T A, Sutherland D S and Nordlander P 2008 Shedding light on dark plasmons in gold nanorings Chem. Phys. Lett. 458 262
[50] Kravets V G, Schedin F, Kabashin A K and Grigorenko A N 2010 Sensitivity of collective plasmon modes of gold nanoresonators to local environment Opt. Lett. 35 956

[51] Blanchard-Dionne A-P, Guyot L, Patskovsky S, Gordon R and Meunier M 2011 Intensity based surface plasmon resonance sensor using a nanohole rectangular array Opt. Express 19 15041

[52] Neumeier L, Quidant R and Chang D E 2015 Self-induced back-action optical trapping in nanophotonic systems New J. Phys. 17 123008