Plasmonic vortex generator without polarization dependence

Han Wang, Lixia Liu, Chunxiang Liu, Xing Li, Shuyun Wang, Qing Xu and Shuyun Teng

The College of Physics and Electronics, Shandong Provincial Key Laboratory of Optics and Photonic Devices, Shandong Normal University, Jinan 250014, People’s Republic of China

E-mail: tengshuyun@sdu.edu.cn

Keywords: optical vortex, surface plasmons, polarization, nanodevice

Abstract

In view of the limitations of vortex generators with polarization dependence at present, we propose a plasmonic vortex generator composed of rectangular holes etched in silver film, in which the optical vortex can be generated under arbitrary linearly polarized light illumination. Two sets of rectangular holes are arranged equidistantly on a circle and rotate in postulate directions. Theoretical analysis provides the design principle for the vortex generator, and numerical simulations give guidance on designing the vortex generator parameters. Experimental measurements verify the performance of the proposed vortex generator. Moreover, two alternative structures for the generation of a plasmonic vortex are also provided in this paper. The resulting perfect vortex, compact structure and flexible illumination conditions will lead to wide applications of this plasmonic vortex generator.

1. Introduction

The optical vortex points to a field with a helical phase front and an annular intensity cross section [1]. Because the vortex beam carries orbital angular momentum, it has potential applications in optical tweezing [2], optical communication [3–5], optical wrenching [6], optical trapping [7–9], information processing [10–12] and other fields. Studies on the generation and manipulation of the optical vortex have attracted much attention. Various conventional generation methods have been suggested such as computer holography [13], helical phase plates [14–16], liquid crystal spatial light modulators [17–19] and optical waveguides [20]. In recent years, the surface plasmonic vortex has been studied based on the excitation of surface plasmon polaritons (SPPs) by nanomaterial structures including plasmonic rings [21, 22], plasmonic Archimedes spirals [23, 24] and plasmonic nanoslits [25, 26], and it manifests its superiority in the micromanipulation of light. A pure vortex to facilitate production as well as convenience of use are the key factors for a perfect vortex generator.

Light beams with spatial symmetry carrying spin and orbit angular momentum are usually chosen as the illuminating light to generate the surface plasmonic vortex. A plasmonic vortex generator (PVG) based on a circular chain of nanoscale annular apertures is proposed, and a spin-dependent plasmonic vortex is created under circular polarization illumination [21]. Split curved slits [26] and gradient-rotation split-ring antenna [27] illuminated by circularly polarized light are also used to generate high-purity vortex beams. The combination of a spiral-shaped grating and a nanometer hole designed on a metal–insulator–metal structure generates a plasmonic vortex and propagates it to the far field [25]. Besides circularly polarized light, vortex beams and radially polarized light are also utilized to generate the plasmonic vortex [22, 28]. Because of the sensitivity of SPP polarization, plasmonic vortex generators under linearly polarized light illumination need a more elaborate design and are usually validated in special polarization directions. An optical vortex generator consisting of a silicon cut-wire array with an azimuthally varied phase profile is proposed, which works in one appointed polarization direction [29]. Nanocavities arranged along an Archimedes spiral are designed to generate the plasmonic vortex and they are validated when the incident light is set in one polarization direction [30]. Even for the plasmonic lens presented by Huang F, the plasmonic vortex is still created under several special
polarizations, and the topological charge of the vortex changes with the incident polarization [31]. The polarization dependence of these plasmonic vortex generators limits their utilization to some degree.

The purpose of this paper is to design a kind of PVG that can produce an optical vortex without polarization dependence and is valid under arbitrary linearly polarized light illumination. Considering the advantages of rectangular holes, including high transmission, anisotropy and convenient manufacture, we choose rectangular holes etched in a metal film to form the PVG. The proposed vortex generator consists of identical rectangular holes etched in the silver film, and these rectangular holes are arranged on one circle. The SPPs excited by rectangular holes form the optical vortex in the center of the PVG and the incident polarization does not change the distribution of the vortex field. Theoretical analysis provides a detailed explanation of plasmonic vortex generation, and the deduced analytical expression also shows the non-destructive role of incident polarization in the vortex field. Numerical simulations based on the finite difference time domain (FDTD) method verify the performance of the proposed PVG. The experimental results conform to the theoretical predictions. In addition, two alternative designs with holes distributed in X and V shapes are also presented to generate optical vortices without polarization dependence. Our novel design means the vortex generator possesses the advantages of ease of manufacture, convenience of use and polarization independence.

2. Basic structure

Our proposed PVG consists of two sets of rectangular holes etched in a silver film with a thickness of $h$, which is deposited on the glass. The number of holes in the two sets is the same, and they are alternately and uniformly distributed on a circle of radius $R$. All the rectangular holes have the same length $l$ and width $w$, yet each hole has a different rotation angle. Figure 1 (a) shows the three-dimensional structure of this PVG and figure 1 (b) shows the two-dimensional structure, where $\alpha_{1n}$ denotes the angle position of the $n$th hole and $\beta_{1n}$ represents the rotation angle of the $n$th hole with respect to the $x$-axis, with $i = 1$ or 2 representing the first or second set of holes.

In our design, the position angle and rotation angle for one set of holes satisfy $\alpha_{1n} = 2n\pi/N$ and $\beta_{1n} = \alpha_{1n} + \alpha_1$ respectively, where the integer $N$ is the number of rectangular holes, $n$ denotes the ordinal number of holes and $\alpha_1$ is a constant angle, and those for the other set of holes satisfy $\alpha_{2n} = (2n + 1)\pi/N$ and $\beta_{2n} = \alpha_{2n} + \alpha_2$ where $\alpha_2$ is another constant angle. The position intersection angle of two adjacent rectangular holes is $\alpha_{2n} = \alpha_{1n} + 2\pi/N$. In order to generate the surface plasmonic vortex in the center of the PVG, the thickness of the silver film, the size of the rectangular hole and the radius of the circle need to be optimized. All these vortex generator parameters can be ascertained based on the FDTD method, and the design principle for the vortex generator is given by the following theoretical analysis.

3. Design principle

In order to create a PVG that is suitable for any linearly polarized light, we start by designing a single rectangular hole. We require that the phase difference of the surface fields at the long and short edge of hole always equals $\pi/2$ with any linear polarization illumination, and use the FDTD method (FDTD solutions) to optimize the thickness of the silver film $h$, the length $l$ and the width $w$ of the rectangular hole. In the practical simulation, the wavelength of the illuminating light is 532 nm, and the dielectric constant of silver is taken from the data given by Palik [32]. The optimized parameters of the hole are $h = 190$ nm, $l = 400$ nm and $w = 200$ nm, respectively.
and figures 2(a)–(c) show the near-field phase distributions of this rectangular hole with 30°, 45° and 60° polarization illumination. The inserted black squares represent the position of the rectangular hole and the black arrows indicate the polarization direction.

From figures 2(a)–(c), it can be seen that all the distributions under different polarization illuminations take on spiral phase structures, and the incident polarization direction only influences the initial position of the spiral phase. This is just the interference result of two surface fields propagating along the long and short edge of the hole. These two surface fields are proportional to the projections of the incident field along the long and short edge of the hole. In fact, it could be equivalent to the radiation of two orthogonal dipoles with a π/2 phase difference, as shown in figures 2(d)–(f), where the red and blue arrows denote dipoles. The red ones have a phase lead of π/2 with respect to the blue ones, and their amplitude ratios are 1.73:1, 1:1 and 0.58:1, respectively, which is close to cos γ cos φ with polarization angles of φ = 30°, 45° and 60°. From figures 2(d)–(f), we can see that the spiral phase distributions of the two orthogonal dipoles are similar to those of the rectangular hole, and the initial position of the spiral phase also changes with the amplitude ratio of the two dipoles (see supporting information 1, available online at stacks.iop.org/NJP/20/033024/medial). Thus, the SP excitation of the hole can be approximately written by $E_0 \cos \varphi + jE_0 \sin \varphi$, where $E_0$ is the incident field and $j$ is the imaginary unit [31].

Next, we devise the SP fields excited by two adjacent holes. Since the longitudinal component of the electric field in the SP field is much larger than the transverse component, here, we are concerned with the longitudinal component of the SP field. Assuming that the angle parameters of two adjacent holes are ($\alpha_{1a}$, $\beta_{1a}$) and ($\alpha_{2a}$, $\beta_{2a}$), as shown in figure 1(b), the SP field coming from the two holes illuminated by the light with the polarization angle γ can be expressed by

$$E_1 = E_0 \left[ \cos \alpha_1 \cos (\alpha_{1a} + \alpha_1 - \gamma) + \cos \alpha_2 \cos (\alpha_{2a} + \alpha_2 - \gamma) \right] + j \left[ \sin \alpha_1 \sin (\alpha_{1a} + \alpha_1 - \gamma) + \sin \alpha_2 \sin (\alpha_{2a} + \alpha_2 - \gamma) \right].$$

Replacing $\alpha_{2a}$ with $\alpha_{1a}$ according to the relation $\alpha_{2a} = \alpha_{1a} + \pi/N$, and rewriting $\alpha_{1a}$ as $\alpha$, we can obtain the relationship of the SP field with the position angle $\alpha$ of the hole and the polarization angle $\gamma$ of incident light. We draw the curves of the real and imaginary parts of the SP field varying with $\alpha$ and $\gamma$, and then fit these curves using the sinusoidal and cosine functions. The real curves and the fitted ones are shown in figure 3, and they are denoted by scattered and solid lines, respectively. The total number of holes is 20; $\alpha_1 = \pi/3, \alpha_2 = \pi/6$; the solid circles denote the real part of the SP field and the hollow circles represent the imaginary part.

The perfect fit of the above curves means the real and imaginary parts of equation (1) can be expressed by the cosine function $1.35E_0 \cos (\alpha - \gamma + \pi/4)$ and the sinusoidal function $1.35E_0 \sin (\alpha - \gamma + \pi/4)$. Thus, we rewrite equation (1) as

**Figure 2.** The phase distributions of a rectangular hole under 30° (a), 45° (b) and 60° (c) polarized light illumination, and of two orthogonal dipoles with a phase difference of π/2 and amplitude ratios of 1.73:1 (d), 1:1 (e) and 0.58:1 (f).
hole size of 400 nm and a circle radius of 2.5 μm. (c) A schematic diagram of the propagation of the SP fields of two holes.

\[ E_i = 1.35E_0[\cos(\alpha - \gamma + \pi/4) + j \sin(\alpha - \gamma + \pi/4)] = 1.35E_0e^{i(\alpha - \gamma + \pi/4)}. \]  

This expression indicates that the SP field excited by two holes with \( \beta_{1n} = \alpha_{1n} + \pi/3 \) and \( \beta_{2n} = \alpha_{2n} + \pi/6 \) is equivalent to one vortex field. Finally, we construct the PVG. Arranging many double holes on a circle, the SP fields excited by all the holes propagate towards the center of the PVG and interfere at a point with the coordinates \((\rho, \theta, z)\), as shown in figure 3(c). According to diffraction theory, the total field near the center of the PVG can be expressed by

\[ E(\rho, \theta, z) = \frac{A}{j\lambda_{app}R}e^{-\kappa z} \int_0^{2\pi} e^{i(\alpha - \gamma + \pi/4)\xi} k_{app}(\rho - r) \, d\xi. \]

where \( A = 1.35E_0\kappa = (k_{app}^2 - k_0^2)^{1/2} \) represents the attenuation coefficient of surface plasmons in air, and \( k_{app} \) is the wave number of the SPPs. Since the directions of \( k_{app} \) and \( r \) are almost opposite for the observation point close to the device center, \( k_{app} \cdot r \) and \( k_{app} \cdot \rho \) can be expressed as \( k_{app} \cdot r = -k_{app}R \) and \( k_{app} \cdot \rho = -k_{app}\rho \cos(\theta - \alpha) \). The total field near the center of the PVG is simplified to

\[ E(\rho, \theta, z) = \frac{A}{j\lambda_{app}R}e^{-\kappa z} \int_0^{2\pi} e^{i(\alpha - \gamma + \pi/4)\xi} e^{-\kappa \rho \cos(\theta - \alpha)} \, d\xi. \]

By means of the integral expression of the Bessel function [33], the above integration can be obtained

\[ E(\rho, \theta, z) = \frac{Ak_{app}}{R}e^{-\kappa z}e^{i(\alpha - \gamma + \pi/4)}j_1(k_{app}\rho). \]

In the above equation, \( j_1 \) represents the first order Bessel function of the first kind. It can be seen from equation (5) that there is a phase term of \( e^{\rho} \), which indicates that an optical vortex with a topological charge equaling \(-1\) has been generated in the center of the PVG. The polarization angle \( \gamma \) only changes the initial phase of the vortex field, and thus our designed plasmonic vortex generator can be used with any linearly polarized light illumination.

It needs to be pointed out that our proposed design can be extended to generate any order of optical vortex. When the rotation angles of holes satisfy \( \beta_{1n} = \alpha_{1n} - \pi/3 \) and \( \beta_{2n} = \alpha_{2n} - \pi/6 \), we can generate the optical vortex with the topological charge equaling \(-1\). If the holes are arranged along the Archimedes spiral with the radial coordinate of holes satisfying \( r = r_0 - m\theta\lambda/2\pi \), where \( r_0 \) is the initial radius and \( m \) denotes an integer, we can obtain a high-order optical vortex with a topological charge equaling \( m \pm 1 \). Moreover, two sets of PVG holes are not necessarily evenly distributed on the circle. The translation of holes along a certain trajectory is also effective, and the alternative PVGs can generate a high-quality optical vortex. Certainly, the designs of these alternative PVGs still satisfy the condition that the combination of holes eliminates the undesirable influence of incident polarization on the optical vortex. In the following content, we show two structures consisting of the PVGs of V-shaped and X-shaped rectangular holes. Perfect optical vortices are also formed using these alternative PVGs.

4. Numerical simulations

In order to examine the performance of the proposed PVG, we simulate its near-field diffraction under different linearly polarized light illumination. Figure 4 gives the simulated results with a silver film thickness of 190 nm, a hole size of 400 nm \( \times \) 200 nm, and a circle radius of 2.5 μm. The position angles of two sets of holes satisfy
\[ \alpha_{1n} = \frac{2n\pi}{10} \quad \text{and} \quad \alpha_{2n} = \left(2n + 1\right)\frac{\pi}{10} \quad \text{with} \quad n \quad \text{being an integer from} \quad 0 \quad \text{to} \quad 9, \quad \text{and the rotation angles satisfy} \]
\[ \beta_{1n} = \alpha_{1} + \frac{\pi}{3} \quad \text{and} \quad \beta_{2n} = \alpha_{2} + \frac{\pi}{6}. \]

The four patterns in the first row of Figure 4 are the electrical field distributions of the PVG on the \(xz\) and \(yz\) planes under \(0^\circ\) and \(90^\circ\) polarization illumination. Figures 4(b) and (d) give the amplitude distributions of the electric field in the \(xy\) plane 250 nm above the silver film with polarization angles of \(0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\) and \(135^\circ\), respectively; figures 4(c) and (e) give the corresponding phase distributions.

From Figure 4(a), we can see that the fringes near the center of the PVG are almost parallel and the fringes along the line at \(x = 0\) and \(y = 0\) are dark. These fringe distributions do not depend on the observation plane or incident polarization. These characteristics are consistent with the distribution rule of the Bessel function, which corresponds to the result given by equation (5). In Figures 4(b) and (d), we can see the regular annular-amplitude distributions, and in Figures 4(c) and (e), we can also see that the spiral phase advances in a counterclockwise direction from \(-\pi\) to \(\pi\). These amplitude and phase distributions do not change with the polarization direction. These distribution rules indicate that the optical vortex is generated by the PVG under any linearly polarized
light illumination. The change of the polarization direction only causes the zero-phase position to rotate. This is consistent with the theoretical prediction. These simulations also verify the performance of our proposed PVG.

5. Experiment

The practical experiment is performed and the experimental setup is depicted as in figure 5(a). Linearly polarized light with a free space wavelength of 532 nm emitted from the laser is converted into circularly polarized light by a quarter wave plate, and then changed into any linearly polarized light by rotating the linear polarizer placed behind it. The PVG sample is illuminated in the glass substrate by the focused linearly polarized light using a microscopic objective with a numerical aperture of 0.6, and the near-field intensity distribution is measured by a scanning near-field optical microscope (SNOM). The probe has an aluminum-coated fiber tip with a 150 nm diameter aperture, which operates in collection mode 100 nm above the Ag film. The PVG sample is implemented with the help of the focused ion beam (FIB) etching method, and figure 5(b) gives the scanning electron microscopy (SEM) image of one designed PVG.

Figure 5(c) shows an SNOM image for the near-field diffraction of the PVG under linearly polarized light illumination with the polarization angle taking 45°, and figures 5(d)–(f) show the magnified intensity distributions near the center of the PVG under 0°, 45° and 90° polarization illumination. We can see that the annular intensity distributions appear in the center of the PVG. The change of the polarization direction has no obvious influence on the intensity distribution, as predicted by the former theory, and these measurement results confirm the performance of the PVG. Carefully observing these measured results, we can see that there is a small bright spot with a low intensity inside the annular intensity distribution. This is different from the theoretical prediction and the result reported previously [26]. We think the reason for this is that the signal detected by the probe contains longitudinal and transverse electric field components. Our theoretical analysis shows that the longitudinal component forms a plasmonic vortex, but the transverse component focuses a weak bright spot (see supporting information 2). As we know, for the small metal-coated SNOM fiber probe, the coupling efficiency of the transverse field is much higher. Although the coupling efficiency of the longitudinal field may increase with the increasing probe aperture size [34], in our experiment, we are still unable to eliminate the weak bright spot because of the lack of a fiber probe with a large caliber.

6. Discussions

In fact, during the optimization process of the PVG structure, we find that the parameters of the designed PVG, including the size of the hole, the thickness of the film and the rotation angle are not unique. Here, we also give another group of parameters, namely the thickness of the silver film 140 nm, the size of the holes 400 nm × 200 nm and the radius of the circle 2.5 μm, respectively. The position and rotation angles of the two sets of holes satisfy $\alpha_{1n} = 2n\pi/10$ and $\alpha_{2n} = (2n + 1)\pi/10$, and $\beta_{1n} = \alpha_{1n} + 7\pi/36$ and $\beta_{2n} = \alpha_{2n} + \pi/18$. 

Figure 5. Experimental setup to detect the near-field diffraction of the PVG using an SNOM (a); an SEM image of the PVG sample (b); the measured intensity distribution of PVG with 45° polarization illumination (c); and the magnified patterns with 0° (d), 45° (e) and 90° (f) polarization illumination.
The near-field diffractions of this equivalent PVG with different polarization illumination are shown in figure 6. The upper patterns are the amplitude distributions with polarization angles of 0°, 30°, 60° and 90° and 135°, respectively, and the lower patterns are the corresponding phase distributions. We can see the annular amplitude and the spiral phase appearing in the center of the PVG. These results indicate that the first order optical vortex can be successfully generated by this PVG under any linearly polarized illumination. The change in the polarization direction causes the zero-phase position to rotate, like the case of the fundamental structure in figure 1.

Moreover, on the basis of the design mechanism of our proposed PVG, we can also design the X-shaped and V-shaped holes to generate surface plasmonic vortices. These two derived PVGs also consist of two sets of identical rectangular holes. Figure 7(a) shows the structure of the PVG with X-shaped holes, where the thickness of the silver film is 290 nm, the position angles of the X-shaped holes satisfy $\alpha_n = 2n\pi/10$ and the rotation angles of the two cross holes satisfy $\beta_1n = \alpha_1n + \pi/6$ and $\beta_2n = \alpha_2n + \pi/3$, respectively. The near-field diffraction amplitude and phase distributions of this PVG are shown in figures 7(b)–(f). It is easy to see that the annular amplitude and the spiral phase appear in the center of the PVG, although the polarization angle takes a different value. The influence of the incident polarization is the same as the former cases.

Figure 8 shows the structure of the PVG with V-shaped holes and its diffraction field distributions. The optimized parameters of this PVG include the thickness of the silver film 110 nm, the position angles of two adjacent holes satisfying $\alpha_1n = \pi n/6 - \pi/30$ and $\alpha_2n = \pi n/6$, and the rotation angles satisfying $\beta_1n = \alpha_1n + \pi/18$ and $\beta_2n = \alpha_2n + \pi/9$. Similarly, doughnut-like distributions also appear at the center of the PVG. The inserted phase distributions have a spiral structure, and this means an optical vortex has been generated. The zero-phase position changes as the incident polarization angle advances in a counterclockwise direction. Certainly, the structure parameters of these two derived PVGs are not fixed, and further simulations of the diffractions of the PVGs confirm this conclusion.

7. Conclusions

In summary, we propose a kind of PVG that is suitable for arbitrary linearly polarized light illumination. This kind of vortex generator consists of two sets of rectangular holes with different rotation angles. The combination of holes eliminates the undesirable influence of the incident polarization on the optical vortex. An optical vortex with any topological charge can be generated by changing the trajectories and rotation angles of the holes. The analytic formula for the diffraction distribution of the vortex generator is deduced based on diffraction theory, and the generation of an optical vortex without polarization dependence is predicted. The numerical simulations and the experimental measurement results prove the performance of our proposed PVGs. Besides the basic structure of the homogeneously distributed holes for the PVG, two alternative structures consisting of X-shaped holes and V-shaped holes are also provided. All of our proposed structures exhibit the advantages of structural simplicity, high vortex quality, convenience of use and polarization independence, and these
Figure 7. A schematic diagram of the PVG with X-shaped holes (a) and its diffraction field distributions with polarization angles of 0° (b), 30° (c), 45° (d), 60° (e) and 90° (f). The inserted patterns are the corresponding phase distributions.

Figure 8. A schematic diagram of the PVG with V-shaped holes (a) and its diffraction field distributions with the polarization angle taking 0° (b), 30° (c), 45° (d), 60° (e) and 90° (f). The inserted patterns are the corresponding phase distributions.
advantages show the benefits of developing PVGs. We think the study in this paper opens up a new way of designing the PVG which will promote applications of the plasmonic vortex in optical integration.

Acknowledgments

The authors acknowledge the support of the National Natural Science Foundation of China under grant no. 10874105 and Shandong Provincial Natural Science Foundation of China under grant no. 2015ZRB01864.

References

[1] Allen L, Beijersbergen M W, Spreeuw R J C and Woerdman J P 1992 Orbital angular momentum of light and the transformation of Laguerre–Gaussian laser modes Phys. Rev. A 45 8185–9
[2] Curtis J E, Koss B A and Grier D G 2002 Dynamic holographic optical tweezers Opt. Commun. 207 169–75
[3] Jia P, Yang Y, Min C J, Fang H and Yuan X-C 2013 Sidelobe–modulated optical vortices for free-space communication Opt. Lett. 38 588–90
[4] Willner A E et al 2015 Optical communications using orbital angular momentum beams Adv. Opt. Photon. 7 66–106
[5] Paterson C 2005 Atmospheric turbulence and orbital angular momentum of single photons for optical communication Phys. Rev. Lett. 94 153901
[6] Simpson N B, Dholakia K, Allen L and Padgett M J 1997 Mechanical equivalence of spin and orbital angular momentum of light: an optical spanner Opt. Lett. 22 52–4
[7] Diererwote M, Mázilo M, Reese P J, Krauss T F and Dholakia K 2008 Optical vortex trap for resonant confinement of metal nanoparticles Opt. Express 16 4991–9
[8] Ng J, Lin Z and Chan C T 2010 Theory of optical trapping by an optical vortex beam Phys. Rev. Lett. 104 103601
[9] Tsai W Y, Huang J S and Huang C B 2014 Selective trapping or rotation of isotropic dielectric microparticles by optical near field in a plasmonic Archimedes spiral Opt. Lett. 14 547–52
[10] Nicolás A, Veissier L, Giner L, Giacobino E, Maxein D and Laurat J 2014 A quantum memory for orbital angular momentum photon qubits Nat. Photon. 8 234–8
[11] Ding D S, Zhang W, Zhou Y Z, Shi S, Xiang G Y, Wang X S, Jiang Y K, Shi B S and Guo G C 2015 Quantum storage of orbital angular momentum entanglement in an atomic ensemble Phys. Rev. Lett. 114 050502
[12] Trichili A, Salem A B, Dudley A, Zghal M and Forbes A 2016 Encoding information using Laguerre–Gaussian modes over free space turbulence media Opt. Lett. 41 3086–9
[13] Carpentier A V, Michinel H, Salgueiro J R and Olivieri D 2008 Making optical vortices with computer-generated holograms Am. J. Phys. 76 916–21
[14] Almazov A A, Elfstrom H, Turunen J, Khonina S N, Soifer V A and Kotlyar V V 2005 Generation of phase singularity through diffracting a plane or Gaussian beam by a spiral phase plate J. Opt. Soc. Am. A 22 849–61
[15] Biener G, Niv A, Kleinert V and Hasman E 2002 Formation of helical beams by use of Pancharatnam–Berry phase optical elements Opt. Lett. 27 1875–7
[16] Genevet P, Yu N, Aïeta F, Lin J, Kats M A, Eleftheriades G V and Hasman E 2015 Plasmonic vortices for wireless communication using plasmonic Archimedes spiral Opt. Express 23 14779–84
[17] Neil M A, Massoumi F, Juskevaitis R and Wilson T 2002 Method for the generation of arbitrary complex vector wave fronts Opt. Lett. 27 1929
[18] Maurer C, Jesacher A, Fürhapter S, Bernet S and Ritsch-Marte M 2007 Tailoring of arbitrary optical vector beams Appl. Phys. Lett. 90 033101
[19] Ostrovsky A S, Kickenstorfparrao C and Arrizn V 2013 Generation of the ‘perfect’ optical vortex using a liquid–crystal spatial light modulator Opt. Lett. 38 534–6
[20] Bai X, Wang J, Strain M J, Johnson–Morris B, Zhu J, Sorel M, O’Brien I J, Thompson M G and Yu S 2012 Integrated compact optical vortex beam emitters Science 338 363–6
[21] Shiirit N, Nechayev S, Kleinert V and Hasman E 2012 Spin-dependent plasmonics based on interfering topological defects Nano Lett. 12 1620–3
[22] Shen Z, Hu Z J, Yuan G H, Min C J, Fang H and Yuan X C 2012 Visualizing orbital angular momentum of plasmonic vortices Opt. Lett. 37 4627–9
[23] Chen W, Abeyingshe D C, Nelson G H and Zhan Q 2010 Experimental observation of microsphere plasmonic lens as a circular polarization analyzer Nano Lett. 10 2075–9
[24] Yang S, Chen W, Nelson G H and Zhan Q 2009 Miniature circular polarization analyzer with spiral plasmonic lens Opt. Lett. 34 3047–9
[25] Garoli D, Zilio P, Gorodetski Y, Tantussi F and Angelis F D 2016 Optical vortex beam generator at nanoscale level Opt. Lett. 41 610–3
[26] Kim H, Park J, Cho S W, Lee S Y, Kang M and Lee B 2010 Synthesis and dynamic switching of surface plasmon vortices with plasmonic vortex lens Nano Lett. 10 529–36
[27] Zeng J, Liu J, Yang X and Jie L 2016 Generating and separating twisted light by gradient–rotation split–ring antenna metasurfaces Nano Lett. 16 13010–8
[28] Cho S W, Park J, Lee S Y, Hwi Kim H and Lee B 2012 Coupling of spin and angular momentum of light in plasmonic vortex Opt. Express 20 10083–94
[29] Yang Y, Wang W, Moitra P, Kravchenko I I, Briggs D P and Valentine J 2014 Dielectric meta–reflectarray for broadband linear polarization conversion and optical vortex generation Nano Lett. 14 1394–9
[30] Chen C F, K C T, Tai Y H, Wei P K, Lin H N and Huang C B 2015 Creating optical near–field orbital angular momentum in a gold metasurface Nano Lett. 15 2746–50
[31] Huang F, Jiang X, Yuan H and Sun X 2016 Generation of plasmonic vortex with linearly polarized light Plasmons 12 1–7
[32] Palik E D 1998 Handbook of Optical Constants of Solids (New York: Academic)
[33] Gradshteyn I S and Ryzhik I M 2014 Table of Integrals, Series, and Products (New York: Academic)
[34] Novotny L and Hecht B 2006 Principles of Nano–Optics (Cambridge: Cambridge University Press)