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On-Chip Discrimination of Orbital Angular Momentum of Light with Plasmonic Nanoslits

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The orbital angular momentum (OAM) of light can be taken as an independent and orthogonal degree of freedom for multiplexing in an optical communication system, potentially improving the system capacity to hundreds of Tbits per second. The high compactness and miniaturization of devices required for optical communications impose strict requirements on discriminating OAM modes of light at a small (micro- or even nano-meter) scale for demultiplexing; these requirements represent a challenge for traditional OAM sorting strategies. Here, we propose a semi-ring plasmonic nanoslit to directly and spatially sort various OAM modes of light into ~120nm-spaced mode intervals on metallic surface. Making use of constructive interference of a helical-phase modulated surface wave excited by a vortex beam, this on-chip interval can be stably demonstrated both theoretically and experimentally with a quasi-linear dependence on the plasmonic wavelength. Furthermore, its immunity to semi-ring geometry (i.e., the radius and number of rings) is verified by simulations. As a result, OAM discriminating is guaranteed by this stable sorting function. This technique shows a viable solution to discriminate the OAM of light at the nano-scale and might lead to broad benefits across the fields of optical communications, plasmonic physics and singular optics.

It was discovered by Allen *et al.* that the orbital angular momentum (OAM) modes of light are associated with an optical vortex having a helical or twisted wavefront of $\exp(il\phi)$, where ϕ is the azimuthal angle and l is the topological charge of vortex¹. The most famous vortex beam with a well-defined OAM of $l\hbar$ (\hbar is the reduced Planck constant) is the Laguerre-Gaussian beam that possesses a series of optical orthogonal eigenmodes, which has been used to demonstrate high-dimension quantum entanglement by violations of Bell-type inequalities^{2,3}. In addition, because of the orthogonality of eigenmodes, the OAM of light introduces a new degree of freedom for multiplexing to enhance the capacity of data transmission systems up to hundreds of Tbits s⁻¹ in optical communications⁴⁻⁷. However, devices in optical communications are usually expected to have small volume for integration purposes⁸⁻¹³, and nanophotonic applications are always based on nano-scale designs¹⁴⁻¹⁸. This imposes a stringent requirement on the challenging fact that these OAM modes at the terminal of a communication system have to be demultiplexed into highly-confined separated spots simultaneously, with a micro- or nano-scale spatial interval between two neighboring modes.

Traditional strategies of sorting OAM modes with bulk optical elements, including the interferometric method^{19, 20}, thermally tuned q-plates²¹, log-polar coordinate transformation²²⁻²⁸, and mimicking Faraday rotation²⁹, arrive at either a large-scale spot for each OAM state, or the separations of neighboring OAM modes with a large interval. However, the reported miniaturized devices for OAM sorting suffer from either allowing only indirect measurement via special interference patterns³⁰ or a limited sorting range^{31, 32}. Therefore, it is urgent to demonstrate a nano-sorter of OAM for demultiplexing in a highly integrated optical communication terminal.

Here, we report a semi-ring shaped nanoslit to serve as a robust and direct OAM sorter that is able to map the OAM modes of light into different subwavelength spots with an on-chip spatial interval of 120nm (at a visible wavelength of 633nm) between each neighboring states. This is achieved by illuminating a circularly polarized vortex beam on the nanoslit to excite and imprint surface plasmon polaritons (SPPs) with a helical wavefront, so that these phase-modulated plasmons are focused into spatially separated subwavelength

spots^{33,34} for different vortices due to constructive interference. The high immunity inherent in the ring geometry makes this approach a viable solution for on-chip discriminating of OAM in many applications such as optical communications and integrated optics.

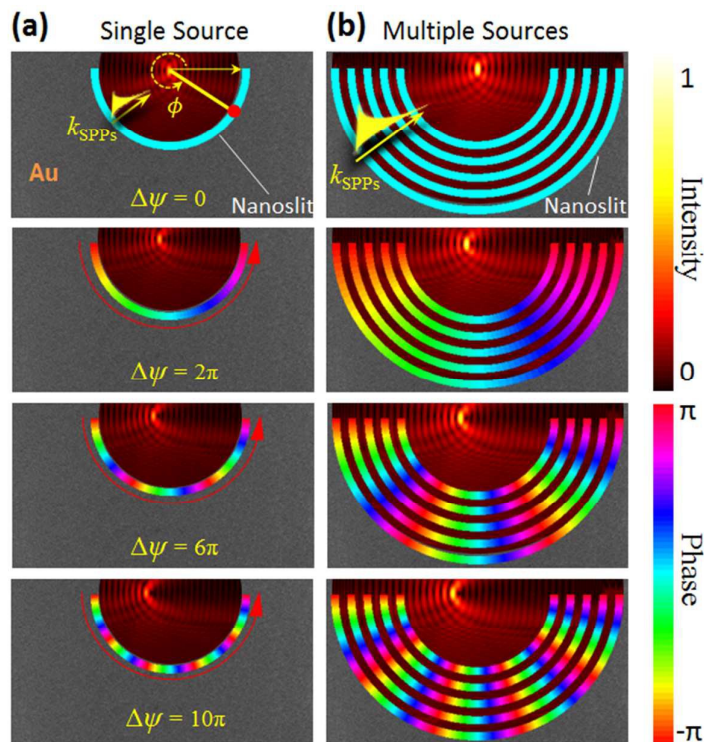


Figure 1 Focal shifts of a semi-circular plasmonic lens after being imprinted with an azimuthal phase. (a) This plasmonic lens is made of a transparent nanoslit that excites the surface wave, forming a semi-circular plasmonic source in gold film. Wavelets from this semi-circular source constructively interfere near the original point of circular source resulting in well-confined focal spot that will shift when semi-circular source is imprinted with an azimuthal (ϕ) phase. (b) Multiple semi-circular sources to enhance the focal spot intensity for easy measurement in experiments.

To demonstrate this mechanism, we show different cases for sources having angular-dependent phase modulation in Figure 1a. Its accumulated phase difference $\Delta\psi$ along the azimuthal direction is defined as $\Delta\psi = \int_{-\pi}^0 \frac{\partial P(\phi)}{\partial \phi} d\phi$, where $P(\phi)$ is the modulated phase of the semi-circular source. In particular, we consider that $P(\phi)$ has the linear dependence on the angle coordinate ϕ because the helical phase of OAM^{35,36} exactly exhibits such required distribution. The employment of OAM is, of course, only one exemplary strategy to

yield such modulated phase. Figure 1a schematically shows transversely shifted focal spots with different locations for $\Delta\psi=0, 2\pi, 6\pi$ and 10π , which implies that the modulation depth of the accumulated phase of the semi-circular source can be indirectly inferred by addressing its corresponding focal position. As a result, this system can be used as an on-chip nano-sorter to discriminate the OAM of light when a vortex beam is illuminated upon such plasmonic nanoslits. In addition, one single plasmonic source (i.e., nanoslits) in the metallic film will increase the difficulties in experimental measurement because of high propagation loss of surface wave so that we adopt five sources to enhance the focal intensity in our experiment, as shown in Figure 1b.

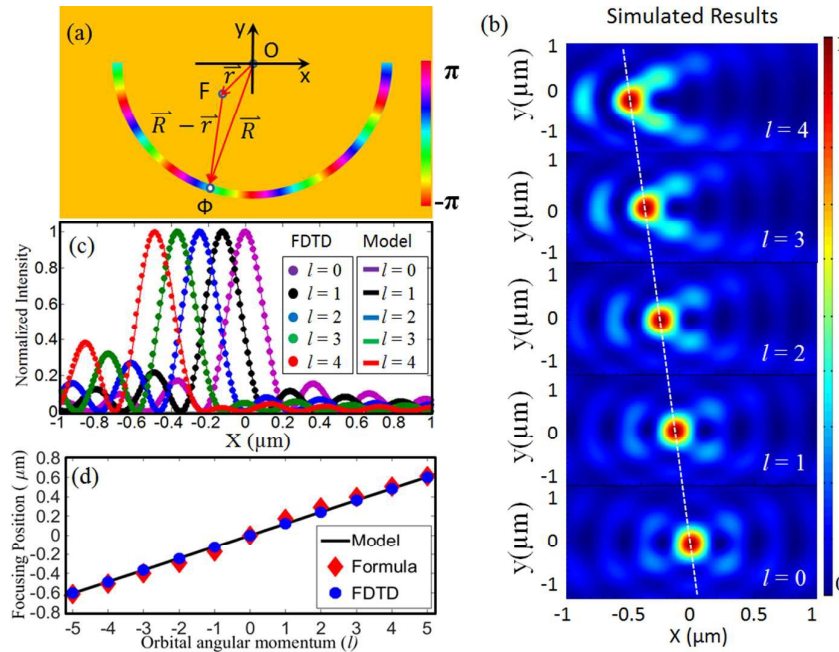


Figure 2 Mechanism, FDTD simulation, and analytical model of the nano-sorter under radially polarized LG beam illumination. (a) Mechanism of the nano-sorter. (b) Simulated focusing positions of different OAM modes using an analytical model. (c) Field distribution fittings by the FDTD simulation (dots) and analytical model (solid lines). (d) Comparison of focusing positions between analytical model (solid line), FDTD (blue dots), and the derived focusing position formula (red diamonds).

Figure 2 shows the mechanism, FDTD simulation, and analytical model to describe the focal spot shifting phenomenon quantitatively. The secondary wavelets on the slit constructively interfere at a certain position along a line radial to the slits to form a focal point.

On the basis of the Huygens-Fresnel principle, we are able to track the surface wave field distribution within the semi-ring shape slits. Considering the incident light has an electric field of $E \propto e^{iP(\phi)} e^{-r^2}$ with radially polarized state, the electric field at the surface is given by

$$U(\vec{r}) = \int_{-\pi}^0 \exp(iP(\phi)) \frac{\exp(ik_{spp}|\vec{R}-\vec{r}|)}{\sqrt{|\vec{R}-\vec{r}|}} d\phi, \quad (1)$$

where \vec{R} is the position vector of any point on a semi-ring slit, \vec{r} denotes the position vector of any viewpoint F , and the original point O is located at the center of the semi-circular slit, as depicted in Figure 2a. Given that the initial phase is merely induced by OAM ($P(\phi) = l\phi$, l is the topological charge of OAM), using Eq. (1), we show the intensity profile for different OAM modes ($l = 0, 1, 2, 3, 4$) calculated by the analytical model in Figure 2b, which unambiguously demonstrates separated focal points along the x direction (i.e., the base of the semicircle). Light beam with $l = 0$ (Gaussian beam) will be focused at the original point O , and the rest will be located in order at the left side. On the other hand, it is expected that all the negative l will be focused at the right side of the center because of symmetry breaking along the azimuthal direction by the semi-ring shaped slit. Larger $|l|$ leads to a bigger transverse shift. Obviously, the number of the sortable OAM states is limited only by the SPPs propagating loss, which is a big advantage when it comes to real applications compared with previous integrated sorters.

More importantly, all the focal points have a subwavelength size in the x direction and are separated in a nearly uniform way with a subwavelength on-chip interval. Due to this small interval compared to the ring diameter, we can further simplify the expression for the electric field along x as $U(x) = J_l(k_{spp}x)$ by employing the paraxial approximation to Eq. (1), such that the position at the peak focal point can be analytically expressed by

$$x_l = \text{sgn}(l) \cdot \chi_l / k_{spp}, \quad (2)$$

where χ_l is the first non-null zero point of $J'_l(x)$ (the derivative of $J_l(x)$) for $l \neq 0$ and $\chi_{l=0} = 0$. This means that the focal positions are totally determined by the topological charge l and the wavelength λ_{spp} of SPPs. In order to verify our analytical model, we simulate the nanoslit

shown in Figure 2a at a wavelength of 633nm through FDTD. The simulated intensity profile along x is shown to have a great agreement with our analytical predictions, which can be observed from Figure 2c. In addition, the distance between any two neighboring OAM modes is about 120nm and the lateral (along x) spot size is about 200nm, which demonstrates a distinguishable separation for different OAM modes. Here we stress that the side band in Figure 2c actually does not increase monotonously with the topological charge as shown in Figure 1S in the Supplementary Material. This provides a feasible solution for sorting the OAM modes of light at the nano-scale. We also display the position x_l of peak intensity of hotspots for different OAM modes with a straightforward comparison among FDTD simulation, theoretical model and the analytical formula of Eq. (2), as shown in Figure 2d. The quasi-linear dependence of x_l on the angular momentum makes our nano-sorter viable for precise discrimination of different OAM modes in real cases. The consistence among the three approaches shows that Eq. (2) excels in the prediction of the spatial shift of hotspots with a simpler form.

So far, the above analysis of on-chip OAM discrimination is based on a single slit without any parameter specification, especially its wavelength independence, which is always considered as a limiting factor. Consequently, a single slit can function as a broadband OAM nano-sorter as long as the incident light's wavelength is smaller than the width of the slit such that SPPs can be excited. As mentioned in Figure 1, in experiments, the employment of a periodic arrangement of slits, instead of a single slit, is mainly for the sake of characterization, because the focal point resulting from multiple slits has much higher energy than that from a single slit. Furthermore, it is preferred to employ circularly polarized light ($\mathbf{E} = e^{i(l+\sigma)\varphi}(\vec{e}_r + i\sigma\vec{e}_\varphi)$) to illuminate the semi-ring slits, because it carries uniformly distributed radial electric field along the azimuthal direction. This allows to uniformly excite SPPs along the slit, and it is more stable compared with the radially polarized beam. Both spin angular momentum (SAM) and OAM can lead to the phase difference along curved gratings³⁷⁻⁴⁰. However, the modulation depth achieved by OAM can be much larger than spin angular momentum (SAM). Although SAM and OAM have quite different physical origins, they arrive at the similar observation—transverse focal point shifts.

As a result, when the vortex beams are circularly polarized, these two strategies will couple together to have a superimposed phenomenon:

$$U(\vec{r}) = \int_{-\pi}^0 \exp(ij\varphi) \frac{\exp(ik_{spp}|\vec{R}-\vec{r}|)}{\sqrt{|\vec{R}-\vec{r}|}} d\varphi, \quad (3)$$

$$x_j = \text{sgn}(j) \cdot \frac{x_j}{k_{spp}}, \quad (4)$$

where σ represents the handedness of the circular polarization (1 for right-handed and -1 for left-handed), and $j = \sigma + l$ is the total angular momentum. Given that the total angular momentum is $j = \sigma + l = -1 + l = 0, 1, 2, 3, 4$, vortex beam with $l = 1$ will be focused at the original point O . As a result, total angular momentum j counts when calculating the transverse focal point shift in this case. This serves as one example of observed equivalence of OAM and SAM⁴¹⁻⁴³. Since the circular polarization state of incident light can be fixed (e.g. $\sigma = -1$) in real applications, the total angular momentum is only dependent on the OAM ($j = l - 1$). So the SAM^{39,40} can be regarded as a dc-component which determines the focal point position of the case $l = 0$. Therefore, that will not affect the function of OAM discrimination as reported in this work.

Figure 3a illustrates the sorting sketch of the proposed semi-rings. A Laguerre-Gaussian (LG) beam with circular polarization is employed to illuminate the semi-ring structure from the quartz substrate side to uniformly excite SPPs along the slits. Periodic semi-rings (period $P=600\text{nm}$) milled into a 200nm -thick gold film on the quartz substrate contain five 300nm -width air-slits to match the plasmon wavelength at an illuminating wavelength of $\lambda=633\text{nm}$, such that a normally incident beam can excite surface waves. Imprinted with a helical phase having a topological charge of l , the surface waves can constructively interfere with each other and finally form a confined spot with a spatial position dependent on l , as shown in Figure 3a. In our fabricated sample, whose SEM image is shown in Figure 3b, the inner and outer radii of the smallest slit are $7.85 \mu\text{m}$ and $8.15 \mu\text{m}$, respectively.

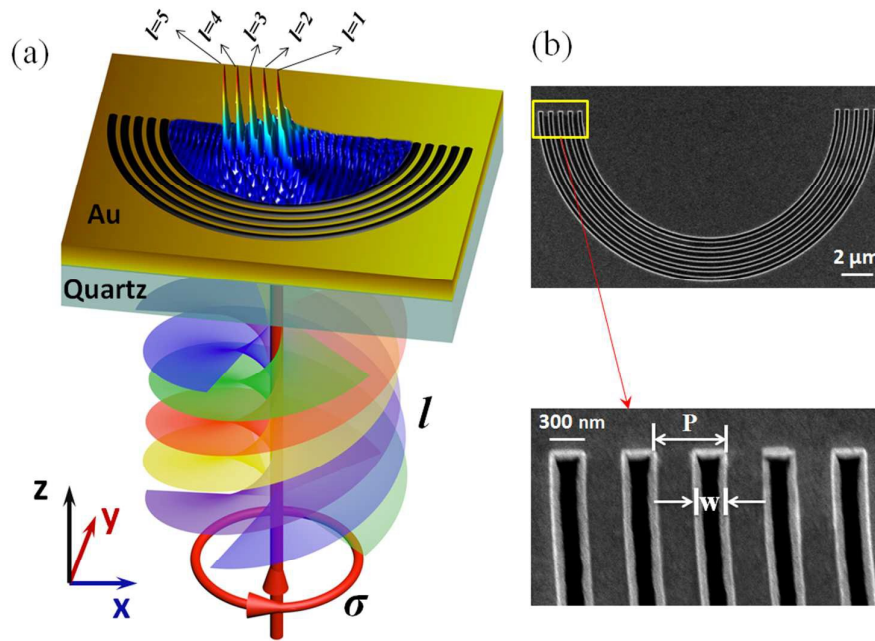


Figure 3 (a) Schematic of launching and sorting multiplexed LG beams. Mixed orders of circularly polarized ($\sigma = -1$) LG beams lead to multiple focal points along a direction radial to the slits whose positions are determined by their topological charge l . (b) SEM image of the nano-sorter and the geometric parameters of the structure. The thickness of the Au layer is 200 nm. The period of the nanoslit is $P = 600$ nm, and the width is $w = 300$ nm.

Figure 4a depicts the experimental setup used to characterize the structure (See NSOM Characterization section for the details). Figure 4b shows the NSOM-measured intensity profiles for different LG beams with topological charges $l = 1, 2, 3, 4, 5$, showing clear hotspots as expected. Line-scanned intensity profiles along the base demonstrate the spatial shifts for different OAM modes, as shown in Figure 4c. Interestingly, there is no side band intensity detected by NSOM which seems to be a discrepancy compared with that of our theoretical model. However, according to the Figure 1S in the Supplementary Material, it can be explained. The reason is that the limited sensitivity and resolution of our NSOM tip may contribute to this discrepancy. Furthermore, the imperfect structure (fabrication issues) will also degrade the performance. Somehow this discrepancy is even an additional advantage, because it helps to reduce the channel crosstalk. In addition, the measured interval between any two neighboring OAM modes is around 120nm in Figure 4d, which coincides with the theoretical value. Illumination of linearly polarized LG beam can further demonstrate our analytical model. Detailed experimental data can be found in Figure 2S in the Supplementary

Material. However, linearly polarized LG beam is unfavorable in practical since it will break the one-to-one relation between OAM modes and focal points.

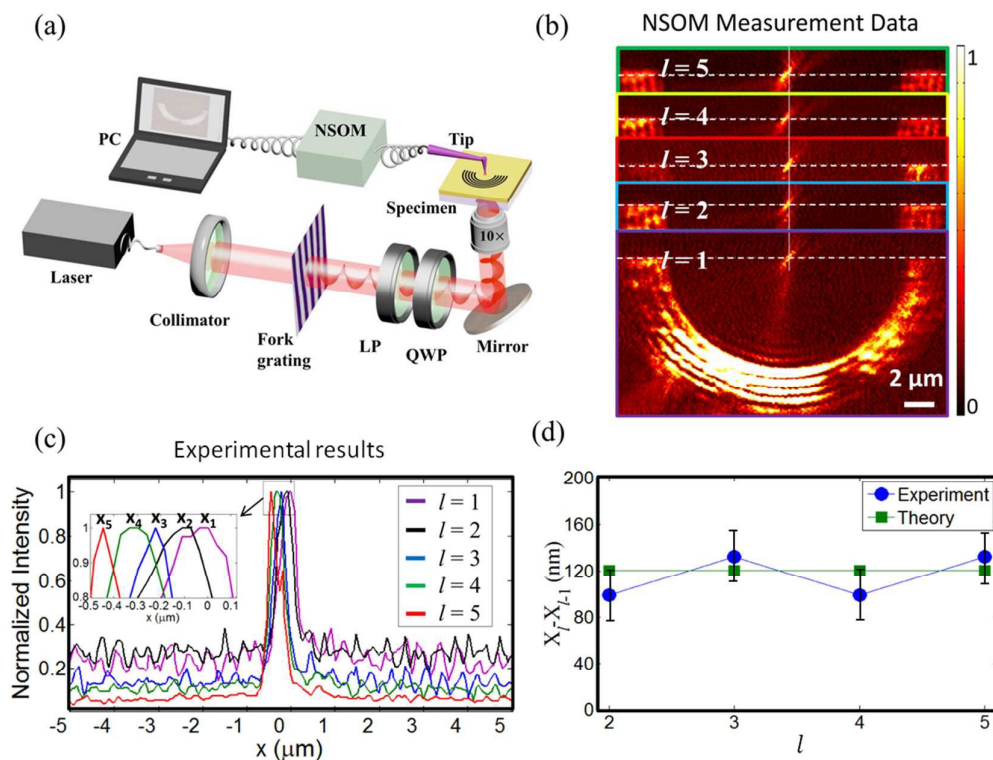


Figure 4 Characterization of the nano-sorter. (a) Experimental setup. HWP: half waveplate, QWP: quarter waveplate. (b) NSOM images of focusing positions for $l = 1, 2, 3, 4, 5$. The vertical white solid line is aligned to the focusing position of the state of $l = 1$. (c) Experimental results of the intensity distributions of different OAM modes along the base (the white dashed lines in (b)) of the slits. (d) Comparison of measured and theoretical interval between any two neighboring OAM modes, the error bar is mainly caused by the diameter of the NSOM tip.

We also investigate its stability for semi-rings with different geometries, i.e., the number of slits and size of inner slit, to show the robustness of our OAM nano-sorter. Without loss of generality, we take the case of $l = 3$ for illustration and carry out the simulations in FDTD. In Figure 5, we can see that the variation of geometry does not influence the spatial shifts of the hotspots, which implies a great stability. However, the increment of slit number enhances the intensity of the hotspots, while this enhancement tends to saturate because of the larger propagation loss of SPPs for the larger-radius semi-ring slits (Figure 5a). On the other hand,

by enlarging the radius of the slits and keeping the ring number fixed, we observe that the intensity of the focal point decreases monotonously (Figure 5b). From the viewpoint of experiment, the LG beam has a donut-shaped intensity profile and its beam radius increases with l . Therefore, multi-slits (five is used in our nano-sorter) are preferred, which enable the focused LG beam to overlay the slits. This immunity to semi-ring geometry makes the discriminating more reliable.

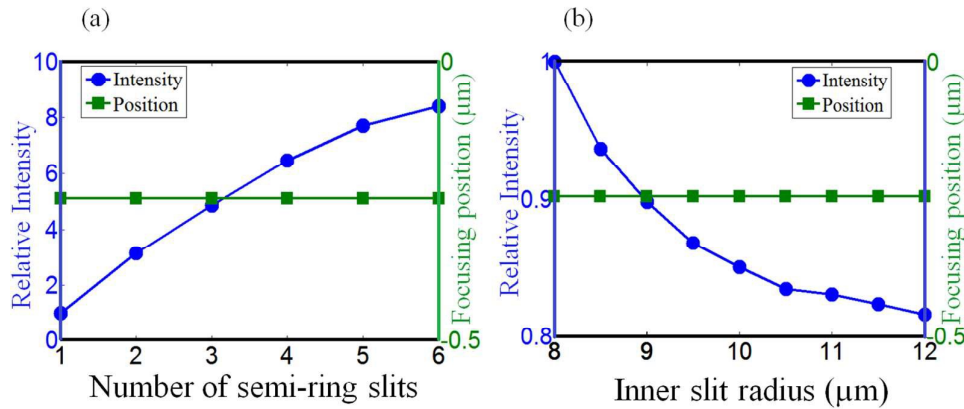


Figure 5 Simulation of the effect of increasing the number of semi-ring slits and inner slit radius on the focal point's intensity and position (the topological charge of the OAM carried by the incident left-handed circularly polarized plane wave is 3). (a) Effect of the number of slits. The inner slit's radius is fixed at 8 μm. (b) Effect of the semi-ring (inner) slit's radius. The total number of the slits is fixed at 5. The inner slit's radius is from 8 μm to 12 μm.

As derived in Eq. (4), the bigger the working wavelength is, the larger the interval between the neighboring two modes will be. In our case, 120 nm interval corresponds to 633 nm incident wavelength, and it will go to 200~400 nm when considering near infrared communication band, which would be easier to separate different modes. Specially, analytical model results of the working wavelength $\lambda=1.55\mu\text{m}$ are presented in Figure 3S in the Supplementary Material which show 310 nm intervals. The calculated crosstalk between the neighboring main bands of OAM modes in current case is about -5 dB (refer to Supplementary Material for the definition of the crosstalk). On the other aspect, interval modes are always suggested instead of consecutive modes, which can largely reduce the crosstalk. For example, $l = 1, 4, 7, 10$ (or even bigger mode interval^{5,7}) will be used as the OAM modes to enhance the system capacity. Under this condition, the crosstalk will be

reduced to -12.1 dB. In addition, analysis of insertion loss of our device can be found in the Supplementary Material. In addition, we are trying to focus different OAM modes into hotspots with a half-round structure rather than receiving them by a detector with a size-limited aperture, so we are not at pain of the singular point in the middle of the vortex beams. Besides, we are inclined to aligned incident beam, which is always required in most nano-devices. Slant incident modes, which are possible to be rectified before the sorter, are not considered here.

The main limitation of this device is that the separation of neighboring OAM modes is relatively small although it is still within the range of resolvability. Future work of increasing the modes' shift may find its solution by employing subwavelength groove waveguides to guide different modes' hot spots away from the rings' center. To be more specific, groove waveguides with period 120 nm can be etched coinciding with the positions of the hot spots. Then the energy of the hot spots can be guided along the waveguides, which can be easily separated (Figure 4S in the Supplementary Material). Another potential strategy of improving the performance is making raised surface in the vicinity of the structure's center. This raised surface can serve as an amplifier to enlarge the space between different modes. However it may increase the fabrication complexity. In addition, based on the same scheme, it is possible to achieve out-of-chip mode sorting (far field sorting) by implementing slits with much larger width based on similar principle, which will also increase the separation.

In conclusion, we have theoretically and experimentally demonstrated the nano-scale separation of OAM of light by a plasmonic nano-sorter composed of semi-ring shaped slits. The significant sorting interval of 120nm between neighboring OAM modes might open a new door to the nano-scale discrimination and manipulation of quantum modes of light. The proposed mechanism based on constructive interference of a phase-modulated surface wave is also useful for general wavefront engineering, which may lead to wide benefits across fields of plasmonic optics, integrated optics and nano-photonics.

NSOM Characterization

The experimental characterization of our OAM nano-sorter is implemented to map the electric field at the surface of gold film by fiber tip-type near-field scanning optical microscope (NSOM, NT-MDT NTEGRA Solaris), as sketched in Figure 4a. The linearly polarized excitation beam originates from a He-Ne laser of wavelength $\lambda = 632.8$ nm (MellesGriot, 25-LHP-925-230). A half-wave plate is utilized to rotate the polarization orientation of the laser beam after the light is emitted out from the laser, then illuminated on holographic fork gratings to create a vertical phase with topological charge $l = 1-5$. The 1st diffraction order of the transmission beams is then selected, and a plano-convex lens with 200mm focal length is used to collimate the vortex beam which creates a doughnut-shaped cylindrical light beam 1mm in diameter. Subsequently, the beam passes through a quarter wave plate that can provide left- and right- circular polarization states. The beam is then focused onto the semi-ring shaped nano-sorter at normal incidence, with the beam spot exactly overlapping the nano-sorter pattern, from the substrate side, by an objective lens (Olympus, UPlanFL 10 \times , NA=0.3). The near-field SPP distribution is obtained by raster scanning the sample surface with an aperture fiber probe 50 nm in diameter. The distance between the fiber tip and sample surface is maintained at few tens of nanometers, which is controlled by a shear-force feedback mechanism. The signal collected by the aperture probe fiber is then guided into a photomultiplier tube (PMT) for recording and amplification.

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