Simultaneous Detection of Spin and Orbital Angular Momentum of Light through Scattering from a Single Silver Nanowire

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In recent times the spin angular momentum (SAM) and orbital angular momentum (OAM) of light have gained prominence because of their significance in optical communication systems, micromanipulation, and sub-wavelength position sensing. To this end, simultaneous detection of SAM and OAM of light beam is one of the important topics of research from both application and fundamental spin-orbit interaction (SOI) point of view. While interferometry and metasurface based approaches have been able to detect the states, the presented approach involves elastic scattering from a monocrystalline silver nanowire for the simultaneous detection of SAM and OAM state of a circularly polarized Laguerre–Gaussian beam. By employing Fourier plane (FP) microscopy, the transmitted scattered light intensity distribution in the FP is analyzed to reconstruct the SAM and OAM state unambiguously. The SAM and OAM induced transverse energy flow as well as the polarization dependent scattering characteristics of the nanowire is investigated to understand the detection mechanism. This method is devoid of complex nanofabrication techniques and to the authors’ knowledge, is a first example of single nano-object based simultaneous SAM and OAM detection. The study will further the understanding of SOI effects and can be useful for on-chip optical detection and manipulation.

1. Introduction
A light beam can possess spin angular momentum (SAM) manifested through its circular polarization state, as well as orbital angular momentum (OAM), manifested through its helical phase front.[1–3] SAM can have two orthogonal states corresponding to left- and right-circularly polarized light, whereas OAM is unbounded with its infinite orthogonal states, corresponding to the topological charge of vortex beams such as Laguerre–Gaussian beams \((LG^m_n)\), \(n\) topological charge, \(m\) radial index).[4,5] This angular momentum of light corresponds to an energy flow in the beam in the transverse plane with respect to the propagation direction, termed as transverse energy flow.[6] Interaction of the transverse energy flow of the beam with a medium may lead to spin-orbit interaction (SOI) induced effects[7–10] such as directional scattering,[11] interconversion of angular momentum[12,13] as well as micro manipulation[14] and position sensing.[15] Additionally, beams possessing SAM and OAM have been envisaged for optical communication,[16–19] quantum information[20] applications due to their orthogonal states.

To this end, deterministic sensing of SAM and OAM has become one of the important topics of research in recent years. Detection of OAM in macroscopic scale has been achieved through conventional interferometry[21–23] as well as diffraction[24–27] and projection through a reciprocal forked diffraction grating.[20] These methods are constrained by their complicated optical setups. With the advancement of nanofabrication, generation as well as detection of OAM and SAM has been achieved at nanoscale.[28–32] At these length scales, the on chip plasmonic devices offer great advancement from the interferometric based techniques with their lower footprint. But, in most cases these devices involve complex fabrication methods.

Thus, there is requirement of methods which are devoid of these complications and possess smaller footprint for chip-scale applications. Additionally, differential sensing of spin and orbital angular momentum component of a light beam using a single nano-object is yet to be achieved. With this motivation, herein we propose a chemically synthesized quasi-1D monocrystalline silver nanowire (AgNW) as a sensor for the simultaneous detection of SAM and OAM of light. AgNWs have gained prominence because of their simple preparation method and monocrystalline characteristics. The solution phase synthesis allows them to be self-assembled on any desired substrate and having necessary tunability.[33,34] The uniform morphology renders them useful for low loss surface plasmon waveguiding property[35] and makes them ideal for fundamental photonic

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circum applications such as plasmonic waveguides,[35,36] plasmonic antennas,[37,38] logic gates[39] as well as for opto-electrical applications. Additionally, in our previous reports we have shown how an AgNW can act as a plasmonic scatterer in sensing total energy flow of an incident beam[41,42] and as well as probing the inherent spin-Hall effect.[43]

In this work, a single AgNW dropcasted on a glass substrate has been used as a nanoscopic strip diffractor and the scattered pattern has been extensively analyzed to ascertain the spin and orbital angular momentum state of the incident light, as shown in Figure 1. By considering the total transverse energy flow, as well as the individual component due to spin flow and orbital flow at the focus, we are able to distinguish their individual effect on the scattering pattern, allowing us to unambiguously determine their value.

2. Results and Discussion

2.1. Theoretical Calculation

In order to distinguish spin and orbital angular momentum, we need to characterize their contribution to the energy flow of the beam.[4] The energy flow of an electromagnetic field, defined by its Poynting vector, can be decomposed into its longitudinal and transverse part. For example, Laguerre–Gaussian (LG) beams, commonly known as vortex beams, possess transverse energy flow corresponding to its orbital flow, owing to its helical wave front. The magnitude and the sense of flow gets dictated by the magnitude and sign of the topological charge of the beam. On the other hand, circularly polarized Gaussian beams exhibit transverse energy flow corresponding to its spin flow, the sense of which gets dictated by the handedness of the circular polarization.

To investigate the interaction due to transverse energy flow at nanoscale, we employ the Debye–Wolf integral formulation[44,45] to find out the optical electric field \( E = (E_x, E_y, E_z) \) and magnetic field \( H = (H_x, H_y, H_z) \) components at the focal plane of a 0.5 NA lens.[46] From these, the corresponding spin flow density (SFD, \( p_\sigma \)) and orbital flow density (OFD, \( p_\pi \)) about z-axis (propagation direction) can be calculated by considering the transverse component (denoted by superscript \( \perp \)) of the following equations\[46\]

\[
\begin{align*}
p_\sigma &= \frac{g}{4\pi} \text{Im}[\nabla \times (\sigma_0 (E^\ast \times E) + \mu_0 (H^\ast \times H))] \\
p_\pi &= \frac{g}{2\pi} \text{Im}[\sigma_0 ((E^\ast \cdot \nabla)E) + \mu_0 (H^\ast \cdot \nabla)H)]
\end{align*}
\]

Figure 1. Schematic of the experimental configuration. An AgNW placed on a glass substrate scatters the incident LG beam to determine its total angular momentum state.

Here \( g = (8\pi)^{-1} \) and \( \omega \) is the oscillating frequency, \( \epsilon_0 \) and \( \mu_0 \) are the electric permittivity and magnetic permeability of vacuum respectively and \( p_\pi \) \( \propto \text{Im}(|\Sigma_i E_i^\ast E_j|) \) (\( i, j = (x, y, z) \)). Figure 2a,b shows the calculated OFD, SFD, and total transverse energy flow density \( (p^\ast = p_\pi^\ast + \pi^\ast) \) corresponding to left-circularly polarized \( \sigma_0 \) and right-circularly polarized \( \sigma_0 \) LG00 beams at wavelength \( \lambda = 633 \text{ nm} \). The total electric field intensity at the focal plane is shown in the inset. As expected, for both \( \sigma_0 \) and \( \sigma_0 \) polarized LG00 beam, the OFD has similar magnitude and similar counter-clock orbital flow sense. But, for \( \sigma_0 \) LG00 beam, the SFD and the corresponding spin flow have both clockwise and counter-clock energy flow in its inner and outer part respectively. Additionally, the magnitude of SFD is higher in its inner radius \( (|p_\sigma| = 1.0858 \text{ at } R = 0.322\lambda) \) and slightly lower in its outer radius \( (|p_\pi| = 0.0731 \text{ at } R = 1.068\lambda) \). It is exactly opposite for the \( \sigma_0 \) LG00 beam. Hence, for \( \sigma_0 \) LG00 beam, counter-clock orbital flow toward the center cancels the clockwise spin flow, whereas, in the outer part the counter-clock spin flow gets added up with orbital flow, resulting an overall counter clock total transverse energy flow having a maximum magnitude of \( |p^\ast| = 0.1515 \text{ at } R = 0.868\lambda \). For \( \sigma_0 \) LG00 the counter-clock inner spin flow gets added up with the counter-clock orbital flow resulting in higher counter-clock transverse energy flow, \( |p^\ast| = 0.2551 \text{ at } R = 0.4\lambda \).

The OFD, SFD and the total transverse energy flow density radial line profile at the focal plane from 0 to 2\( \lambda \) corresponding to \( \sigma_0 \) and \( \sigma_0 \) polarized LG00 beams are shown in Figure 2c,d respectively. In this context, it is important to point out the subtle differences of the intensity profile for \( \sigma_0 \) and \( \sigma_0 \) polarized LG00 beams as focusing of circularly polarized LG beam aids spin-to-orbital angular momentum transformation.[12] The field calculations and corresponding phase profiles are shown in the Section S1, Supporting Information.

2.2. Experimental Implementation

The focal optical field and its orbital and spin flow constituents, upon interaction with a nano structure will lead to flow dependent scattering allowing us to determine its state. Although different nano-structures have been shown to have exhibited transverse energy flow dependent scattering,[50,51,41,42] differential sensing of spin and orbital flow is yet to be achieved by a single nano-object. To that end, we use a single crystalline AgNW to scatter the incident optical field and sense its properties. The implementation of forward scattering configuration is achieved
Figure 2. Theoretically calculated focal orbital flow density (OFD), spin flow density (SFD), and total transverse energy flow distribution for a) left-circularly polarized ($\sigma_+$) and, b) right-circularly polarized ($\sigma_-$) $LG_{10}$ beam. Inset shows the corresponding total field intensity. c,d) represents the OFD, SFD, and total transverse energy flow distribution line profile along $x$-axis from 0 to 2\( \lambda \).

Figure 3. a) Experimental configuration for measuring the Fourier plane (FP). Inset shows the bright field optical micrograph of AgNW. Experimentally measured Fourier plane intensity distribution for scattering of b) $x$ polarized and c) $y$ polarized $LG_{10}$ beam. Inner and outer white circles represent the critical angle at the air-glass interface and the collection limit of the objective lens NA respectively. Incident NA region is blocked and appears as a black disk at the center. d) Simulated near-field electric field intensity distribution at the air-glass interface for $x$ and $y$ polarized incident beam. e) Corresponding scattered total transverse energy flow density ($p^{\perp\text{scat}}$) distribution for $x$ and $y$ polarized $LG_{10}$ beam. The black arrows indicate the energy flow direction.

by dropcasting AgNWs of width $\approx 350$ nm onto a glass cover-slip, which acts as a nanoscopic strip scatterer\cite{24,27} for the incident optical fields. A 50 x 0.5 NA objective lens has been used to focus the incident beam and the scattered signal was collected using a 100 x 1.49 NA lens, in the transmission configuration (Figure 3a). A low power of 0.13\( \mu \)W has been used for the scattering of $LG_{21}^0$ beam. Fourier plane (FP) intensity distribution of the forward scattered light was collected by projecting the back focal plane of the collection objective lens onto a CCD using relay optics.\cite{48,49} The collected FP intensity distribution can be divided
into two regions, sub-critical region (NA < 1) and super-critical region (NA > 1). The incident NA part (NA 0 – 0.5) in the sub-critical region is dominated by the un-scattered incident light, and is omitted from our analysis, appears as a black disk at the center of the measured FP. Details of the experimental configuration is elaborated in the Section 4 and Section S2, Supporting Information.

2.3. Polarization Dependence of Scattering Intensity

To determine the contribution due SAM and OAM in the scattered FP, it is imperative to understand the scattered FP patterns and distribution of its constituent linear polarization components. The longitudinally polarized optical field ($E_x$) with respect to the nanowire long axis (x axis) gets scattered in the sub-critical region, as shown in the experimentally measured data in Figure 3b for x polarized LG1^0 beam. On the other hand, the transversely polarized fields ($E_y$) lead to near-field (NF) at the NW edges, and consequent signal at the super-critical region in the FP as well as sub-critical region, shown in Figure 3c for y polarized LG1^0 beam. Additionally, the polarization of the scattered light for the x polarized incident beam is predominantly x polarized and similarly, for y polarized beam scattering, the light scattered in the sub- and super-critical region is mostly y polarized (Section S3, Supporting Information). Thus, for scattering of circularly polarized LG1^0 beam, the state of circular polarization can be determined by analyzing the sub-critical region intensity distribution as only in this regime both in-plane x and y components of polarization scatter. Whereas, in super-critical region, predominantly scattered light is from y polarized field and will possess information about OAM state of the incident beam. This has been further confirmed by analyzing the FP due to y polarized LG1^0 beam (Section S3, Supporting Information), where upon analyzing the FP intensity distribution for x and y polarized components, we can recover the FP intensity distribution for x and y polarized intensity distribution as shown in Figure 3b,c respectively. It must also be observed that both FP intensity distribution for x and y polarized LG1^0 beam exhibit two lobes as well as preferential scattering pattern due to their orbital flow. But, the preference for x polarized case is opposite to that of y polarized case. This can be attributed to the polarization dependent interaction of the NW with the incident beam as shown through numerical simulation in Figure 3d,e. The details of the finite element method numerical simulation and geometry is given in Section S4, Supporting Information. For x polarized LG1^0 beam the field gets scattered from the NW and the corresponding total transverse energy flow ($p_{trans}^{x}$) points away from the NW and opposite to the incident beam p^0. On the other hand, y polarized LG1^0 beam aids the interaction of the transverse energy flow with the nanowire and leads to generation of evanescent nearfield at nanowire edges, apparent with the presence of scattered light signal in the super-critical region of FP in Figure 3c. Consequently, the scattered field $p_{trans}^{x}$ flow is along the same direction as that of the incident beam. Thus, a nanowire through its scattering can detect OAM modes as well as its linear polarization states. The effect is qualitatively similar to a nanoscopic strip scatterer.  

2.4. Nanowire as a Sensor for OAM and SAM State

Next, we investigate the FP intensity distribution for $\sigma_+$ and $\sigma_-$ polarized LG1^0 beam to determine OAM and SAM state of the beam. Figure 4a,b shows the FP intensity distribution for $\sigma_+$ and $\sigma_-$ LG1^0 beam, respectively. We analyze the pattern by dividing the FP into four parts and looking into the intensity distribution of either upper ($k_y > 0$ region) or lower half ($k_y < 0$ region). Additionally, the SAM and OAM signature can be obtained by analyzing the signal in the super-critical and super-critical region intensity distribution respectively. Figure 4c,d shows the intensity distribution profile within the sub-critical region of the $k_y > 0$ part in the FP, for $\sigma_+$ and $\sigma_-$ polarized LG1^0 beam, respectively. The preference of the scattering is opposite for $\sigma_+$ polarized LG1^0 beam scattering with respect to that of $\sigma_-$ LG1^0 beam data as indicated by the black arrows. The preference is the result of spin flow. Since the dominant contribution to the spin flow occurs due to the inner circular part of the beam as shown in Figure 2, the preference follows the same handedness. The super-critical region intensity distribution profile in the $k_y > 0$ half for both $\sigma_+$ and $\sigma_-$ polarized LG1^0 beam exhibit similar preference as shown in Figure 4e,f. This preference as well as the number of lobes indicates the OAM state of the incident beam.  

The intensity distributions can be further quantified by calculating the directionality, $D = (I_1 - I_2)/(I_1 + I_2)$, where $I_1$ represents the integrated intensity of i'th lobe for sub- or super-critical region. From the experimentally measured data in Figure 4c,d we find, $D_{sub} = 0.094$ for $\sigma_+$ LG1^0 beam and $D_{sub} = -0.123$ for $\sigma_-$ LG1^0 beam in the sub-critical region. Thus, $D_{sub} > 0$ for $\sigma_+$ polarization case and $D_{sub} < 0$ for $\sigma_-$ polarized beam, that is, sign of the directionality in the sub-critical region inverts depending upon the spin flow direction and hence the SAM state. On the other hand, the preferential scattering in the super-critical region of the FP indicates the sense of orbital flow and hence the OAM state: $D_{super} = -0.284$ for $\sigma_+$ polarized and $D_{super} = -0.563$ for $\sigma_-$ polarized LG1^0 beam, that is, directionality sign ($D_{super} < 0$) remains the same. Hence, $D_{sub} > 0$ and $D_{super} < 0$ indicates $\sigma_+$ LG1^0 beam excitation and $D_{sub} < 0$ and $D_{super} < 0$ indicates $\sigma_-$ LG1^0 beam excitation. Although the differential sensing of the orbital and spin flow is achieved, the total transverse energy flow influences the effective directionality magnitude in the super-critical region to some extent. The measured directionality for the super-critical region is significantly lower for $\sigma_+$ LG1^0 beam than for $\sigma_-$ LG1^0 beam, which is due to the higher total transverse energy flow density for $\sigma_-$ polarized beam, as shown in Figure 2. For sub-critical region the change is much smaller due to lower directionality value as well as positional sensitivity. The directionality values will be exactly opposite in sign when we consider the lower half ($k_y < 0$ region) of the scattered FP intensity distribution as the intensity pattern for $k_y > 0$ region is anti-symmetric with respect to $k_y < 0$ region (Section S5, Supporting Information).

The detection mechanism is robust with respect to the inversion of the orbital flow. We prove this by investigating the scattered FP intensity distribution for $\sigma_+$ polarized and $\sigma_-$ polarized LG1^0 beam as shown in Figure 5a,b, respectively. The corresponding intensity distribution profile in sub-critical region of the the $k_y > 0$ half for the $\sigma_+$ and $\sigma_-$ polarized case is shown in Figure 5c,d, respectively. The measured directionality
is found to be \( D_{\text{sub}} = 0.054 \) for \( \sigma_+ \) and \( D_{\text{sub}} = -0.132 \) for \( \sigma_- \) polarized \( LG_{-1}^{+} \) beam. The preference of scattering in this region is same as that of the \( \sigma_+ \) and \( \sigma_- \) polarized \( LG_1^0 \) beam, indicating the same SAM sign. Whereas, for the super-critical region, the intensity distribution profile shown in Figure 5e,f (\( D_{\text{super}} = 0.369 \) and \( D_{\text{super}} = 0.114 \)), the preference is opposite to that of the \( LG_0^0 \) case, indicating the sign inversion of the topological charge and hence the orbital flow as well as total transverse energy flow of the beam. Therefore, owing to the polarization and transverse energy flow dependent interaction of the AgNW with the incident beam, we are able to unambiguously detect OAM and SAM of the incident beam. The accuracy of the simultaneous detection of the SAM and OAM state depends upon the width of the nanowire used for the scattering process. We have performed the experiments for nanowires having width \( \approx 200 \) nm, and the results have been elaborated in Section S6, Supporting Information. In general, the directionality in the sub- and super-critical region depends upon the incident polarization state of the beam. For \( LG_1^0 \) beam, the elliptical polarization dependence of the directionality and the reconstruction of elliptical polarization states are investigated in Section S7, Supporting Information.

2.5. Detection of OAM and SAM for Higher Order LG Beam

Next, we explore the possibility of simultaneous detection of higher order OAM as well as SAM and investigate the FP intensity distribution for higher order LG beam: \( LG_n^m \) beam.

The corresponding intensity distribution profile in the sub-critical region of the \( k_x > 0 \) part of the FP for \( \sigma_+ \) and \( \sigma_- \) polarized \( LG_1^0 \) beam shown in (c) and (d), respectively. The black arrows indicate the effective directionality.
Figure 5. Experimentally measured scattered FP intensity distribution a) $\sigma_+$ and b) $\sigma_-$ $\text{LG}_{10}^0$ beam. The corresponding intensity distribution profile in the sub-critical region of the $k_y > 0$ part of the FP for $\sigma_+$ and $\sigma_-$ polarized $\text{LG}_{10}^0$ beam is shown in (c) and (d), respectively. The same for super-critical region is shown in (e) and (f). The black arrows indicate the effective directionality.

Figure 6. Experimentally measured scattered FP intensity distribution of a) $\sigma_+$ polarized and b) $\sigma_-$ polarized $\text{LG}_{20}^2$ beam. The corresponding intensity distribution profile in the sub-critical region of the $k_y > 0$ part of the FP for $\sigma_+$ and $\sigma_-$ polarized $\text{LG}_{20}^2$ beam is shown in (c) and (d), respectively. The same for super-critical region is shown in (e) and (f). The black arrows indicate the effective directionality.
tered width (k = −0.5 to 0.5) in the FP intensity distribution, will make it harder for us to detect the fluctuations in the polarization dependent magnitude of the lobes.

3. Conclusion

To summarize, we have experimentally shown how forward scattering from a single AgNW can be used for simultaneous unambiguous sensing of spin and orbital angular momentum by employing Fourier plane microscopy. By analyzing the intensity lobes due to circularly polarized LG beam in the sub- and super-critical region in the Fourier plane, we show that the preference of scattering in the sub-critical region changes when the spin is inverted, whereas the super-critical region intensity distribution preference depends predominantly on the orbital energy flow of the incident beam, thus allowing an unambiguous detection of both. The incident linear polarization dependent behavior of the AgNW of scattering within the sub-critical region or both sub- and super-critical region in the FP, allows the detection mechanism. The focal optical field calculation gives us more insight onto the scattering mechanism as well as the resulting directionality. Thus, our work emphasizes spin-orbit interaction based simple single element chip-scale detection configuration with prominent spin and orbital angular momentum detection capability. Additionally, the spin-orbit interaction dependent scattering may lead to opportunities in harnessing the resulting optical forces for optical manipulation at nano scale as well as furthering our understanding of spin-orbit interaction.

4. Experimental Section

**Experimental Measurement:** The forward scattering measurements were performed using a home-built dual-channel Fourier microscope. A 50x 0.5 NA objective lens (Olympus) was used to focus the incident light on a silver nanowire dropcasted glass coverslip placed on a piezo stage (PI P-733.3CD XYZ Piezo Nanopositioner). The scattered light had been collected using 100x 1.49 NA lens and projected to the CCD (Thorlabs) using relay optics. A spatial light modulator (Holoeye LC-R 2500 SLM) with off-on a silver nanowire dropcasted glass coverslip placed on a piezo stage was performed using a home-built dual-channel Fourier microscope. A coverslip for use.

**Sample Preparation:** The thick silver nanowires (diameter ≈ 350 nm) were synthesized using seeded polyol process outlined in ref. [34]. The synthesized nanowires were cleansed by centrifuging them in acetone (4000 rpm for 5 min) and then in ethanol (4000 rpm for 5 min). Finally a dilute amount of NWs were dispersed in ethanol and dropcasted on a glass coverslip for use.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Keywords**

spin-orbit interactions, angular momentum of light, singular optics, Fourier plane imaging

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