Near-field probing the magnetic field vector of visible light with a silicon nanoparticle probe and nanopolarimetry

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Abstract: Magnetic light-matter interaction plays a crucial role in nanophysics, such as in photonic topological insulators and metamaterials. Recent advances in all-dielectric nanophotonics especially demand vectorial mapping of magnetic light at visible wavelengths. Here, we report that a novel functional nanoprobe decorated with a silicon nanoparticle predominantly senses both the vertical and lateral magnetic field, that is, the magnetic field vector, complementary to a metal nanoparticle probe detecting the local electric field vector. As a proof-of-principle experiment, we demonstrate the mapping of magnetic field vectors in a transverse electric (TE) evanescent standing wave by this probe in a scanning near-field optical microscope (SNOM) with nanopolarimetry. It is for the first time that the full magnetic field vector of visible light, whose frequency exceeds 550 THz, can be directly detected with deep subwavelength resolution. Such functional probe and nanopolarimetry may pave the way toward complete vectorial near-field characterization over the whole visible band for nano-optics and subwavelength optics.

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1. Introduction

Light is an electromagnetic wave that contains both the electric and magnetic field vectors. Mostly, the electric light-matter interaction prevails over the magnetic one [1]. However, as light interacts with nanomaterials or nanostructures, the magnetic interaction may become predominant at the nanoscale, such as in the studies of negative-index metamaterials [2, 3], toroidal dipole and anapole excitation [4, 5], and Fano resonance [6, 7]. Particularly, due to the optically induced Mie response of the high-index nanostructures, the magnetic interaction may play an essential role in all-dielectric nanophotonics [8–11] so that the optical magnetic field can reveal the physical insight of nanodevices, such as the magnetic coupling in waveguides [12] and the directional surface states in photonic topological insulator [13]. The interaction between light and nanostructures leads to intricately vectorial distribution of light field at the nanoscale. Thus, probing and mapping the near-field distributions of magnetic field vector have vital importance for both nanoscience and nanotechnology.

Scanning near-field optical microscopy (SNOM) has been widely used to characterize the near-fields of nanostructures with deep subwavelength resolution [14] because of its advantageous feature to visualize the distributions of the electric vector [15–19]. The nanoprobe is the key element in SNOM, acting as an optical antenna [20–22] that converts the evanescent waves into propagating waves and vice versa. For the detection of magnetic fields, some probes with different principles and geometries have been proposed, such as the split-ring probe [23] for detecting vertical magnetic field, the Bethe-hole probe [24–26] and the hollow-pyramid probe [27, 28] for
detecting lateral magnetic field, and the probe with rare earth ions [29] for detecting magnetic intensity. Besides, several indirect measurement methods for reconstructing the magnetic field have also been proposed, such as the curl of measured electric field [30], the perturbation theory in photonic cavities [31–33], and the use of the Babinet’s principle [34] and reciprocity of electromagnetism [35–37].

Despite the above-mentioned methods, some restrictions exist for mapping and visualizing the complete magnetic vector of light. Indirect measurement methods strongly rely on the measured structures whose mode distributions or symmetries provide a priori knowledge to ensure the accuracy of the reconstruction. Thus, direct measurement methods based on functional probes hold great potential for universally probing the magnetic vector of arbitrary nanostructures. However, a key challenge is that few probes can sense the magnetic field of light with oscillating frequency exceeding 550 THz. This challenge originates from the saturation of the magnetic response of split-ring antennas [38], the invalidity of the Leontovich boundary condition [24], and the limitations of the top-down fabrication, to name a few. Besides, the existing functional probes can only sense either the vertical or lateral magnetic field components. Therefore, it is still an open question of how to directly probe the complete magnetic vector with deep subwavelength resolution over the whole visible spectrum. Recently, it has been reported that silicon nanoparticles (SiNPs) have significant optically induced magnetic responses at visible wavelengths [39,40], and a free SiNP can detect the magnetic transverse spin angular momentum (SAM) of a focused cylindrical-vector beam [41], indicating that a probe combined with a SiNP may be a promising solution to address the fundamental question.

Here, we propose a novel functional nanoprobe attaching a SiNP using a bottom-up approach, allowing the direct measurement and visualization of magnetic field vector. As a demonstration, a transverse electric (TE) evanescent standing wave generated by total internal reflection (TIR) is used to distinguish the magnetic vector from the electric vector. A vectorial near-field microscope based on SNOM system is proposed for continuously measuring the local Stokes parameters of near field with deep subwavelength resolution, i.e., nanopolarimetry. Using the functional probe and nanopolarimetry, we show for the first time that the SiNP probe can directly measure and visualize the magnetic field vector of visible light, which is complementary to the existing metal nanoparticle probe for detecting the electric field vector [15]. Besides, we apply the reciprocity of electromagnetism to interpret the measurement mechanism of the magnetic vector and analyze the influence of the electric interaction of the probe-field system.

2. Results and discussion

2.1. Transverse electric (TE) evanescent standing wave distinguishing between the magnetic and electric dipole radiations

In SNOM measurement, the probe converts the near field into the far field. Though the detectors can only sense the far-field electric field, this electric field can originate from both the electric and magnetic near field. For reasonably distinguishing between the magnetic and the electric near field in our experimental demonstration, a determination field, whose electric and magnetic components spatially separate well, should be elaborately selected. Focused cylindrical-vector beams [25,29] and evanescent waves in waveguides [23] or cavities [31,32] are effective candidates. Besides, the propagating light in free space with an oblique incidence [24–26] can also identify whether the dominant component is magnetic or not, because the lateral projection of the electric and magnetic fields are no longer perpendicular. Here, we choose a TE evanescent standing wave as the determination field, which contains two counter-propagating s-polarized
evanescent light fields by total internal reflection (TIR) in a right-angle prism and satisfies

$$
\begin{align*}
    cB_x &= \sqrt{n^2 \sin^2 \theta' - 1} E_0 \sin (k_x x) \exp (-\gamma z) \\
    E_y &= i E_0 \sin (k_x x) \exp (-\gamma z) \\
    cB_z &= n \sin \theta' E_0 \cos (k_x x) \exp (-\gamma z)
\end{align*}
$$

(1)

where $E_0$ is a constant magnitude, $k_x$ and $\gamma$ are wave vector components related by $k_x^2 - \gamma^2 = (\omega/c)^2$, $k_x$ is the lateral wave vector and satisfies $k_x = (\omega/c) n \sin \theta'$ where $n$ is the refractive index of the prism (e.g., $n = 1.52$ at 532 nm for BK7 glass) and $\theta' = 45^\circ$ is the incident angle. Figure 1(a) describes the distributions of the field vectors according to Eqs. (1), where the green and red arrows represent the magnetic and electric field vectors, respectively.

![Figure 1](image)

From the view of power coupling, the detected far-field signal $E_{FF}$ scattered by the nanoprobe can be expressed by near-field electromagnetic fields $\{E_{NF}, H_{NF}\}$ together with the induced dipole moments $\{p, m\}$ as $E_{FF} \approx -p \cdot E_{NF} + m \cdot B_{NF}$ [42]. Thus, the near-field detection process by a nanoparticle probe in Fig. 1(a) can be interpreted by a dipole radiation model. Local TE near field $\{E_{NF}, H_{NF}\}$ generates effective dipole moments $\{p, m\}$ in the nanoparticle, where the electric and magnetic dipole moments are parallel to the TE electric and magnetic field vectors, respectively. Then, the induced dipole moments radiate to the far field and the detected electric field vector $E'$ in the $xy'z'$ coordinate can be expressed as (cf. Appendix A)

$$
E' \propto \begin{pmatrix}
    m \sin \Psi \\
    0 \\
    -m \cos \Psi
\end{pmatrix}
\begin{pmatrix}
    m \theta \sin \Psi \\
    0 \\
    2 \epsilon p
\end{pmatrix},
$$

(2)

where $y'$-axis is the optic axis of the far-field radiation, $\theta$ and $\Psi$ in radians are the pitch angle between $y$-axis and $y'$-axis [cf. Fig. 1(b)] and the orientation angle of the magnetic field vector relative to $x$-axis [cf. Fig. 1(c)], respectively.

For a probe with a negligible magnetic response (i.e., $m/c \ll p$), such as the gold nanoparticle probe [15] and the bare fiber tip [43], the radiated electric field vector $E'$ only has a $z'$-component
based on Eq. (2), which is a projection of $E_y$ in Eq. (1), as illustrated in Fig. 1(b). On the contrary, for a probe with a strong magnetic response (i.e., $m/c \gg p$), the radiated electric field vector $E'$ is almost perpendicular to the near-field magnetic field vector with a minor angle difference based on Eq. (2). This difference results from the pitch angle $\theta$, and is less than $5^\circ$ even for a larger angle $\theta = 30^\circ$, as shown in Fig. 1(c). The pitch angle equals $15^\circ$ in our measurements, so it is reasonable to consider the far-field electric field vector perpendicular to the near-field magnetic field vector. To conclude, when probing the near field of the TE evanescent standing wave with a nanoprobe along $x$–direction, the probe senses the electric field if the detected far-field electric field vectors maintain the directions along $z'$–axis; otherwise, the probe senses the near-field magnetic field vector if the detected electric field vectors rotate along the $x$–direction.

2.2. Functional SiNP probe and vectorial near-field microscope with nanopolarimetry

According to our previous study [42], a nanoprobe can sense the local magnetic field of light provided this nanoprobe can support a strong magnetic dipole (MD) moment illuminated by the light with the same frequency. SiNPs with sizes of a few hundreds of nanometers are able to generate magnetic resonance at the visible spectrum with small losses [39, 40]. Thus, the SiNP is the most critical element of the proposed functional nanoprobe for detecting the magnetic field of light in the visible band. SiNPs can be conveniently fabricated by laser ablation method [44] or printing method [45], so we use laser ablation method to fabricate separate SiNPs and use a home-built dark-field microscopic and spectroscopic system to select SiNPs with desired resonance wavelengths (cf. Appendix B). Figure 2(a) illustrates a dark-field spectrum of one selected SiNP where the green and red areas are generated by a two-peak fitting of the experimental data (blue curve), indicating radiations from the magnetic dipole (MD) and electric dipole (ED) moments, respectively. For comparison, a simulation with a SiNP positioned onto a glass substrate is performed (by FDTD solutions 8.11, Lumerical Co.) and shown in Fig. 2(a). The simulated dark-field spectrum (black curve) is in good consistent with the measured one (blue curve), indicating an obvious MD resonance around the wavelength of 580 nm. In the simulation, the SiNP is set with diameter 144 nm surrounded by a 10 nm surface dioxide layer, and the dielectric function of silicon was taken from Palik [46]. To make the simulation match the dark-field situation, the scattered light in the substrate is omitted.

The functional SiNP probe can be fabricated with a bottom-up approach as follows [47, 48]. First, a parabolic fiber probe (cf. Appendix C) was successively prepared by heating-pulling of a commercial single-mode fiber [cf. Fig. 2(b)] and chemical etching [cf. Fig. 2(c)]. This fiber probe aims to manipulate the SiNP freely in three-dimensional (3D) space with nanometer resolution, and the parabolic shape is adopted to shorten the length of the tip and improve its robustness. Second, the parabolic fiber probe was made clean and hydrophilic by a solution (NH$_3$ : H$_2$O : H$_2$O$_2$ : DI water = 1 : 1 : 5) in 80 °C water bath [cf. Fig. 2(d)] for 15 minutes. This procedure aims to enhance the adhesion between the fiber probe and the chemical crosslinker (e.g., APTES). Third, the hydrophilic fiber probe was immersed into an organic solution (APTES : IPA = 1 : 9) for 15 minutes for coating with a layer of the crosslinker [cf. Fig. 2(e)]. Finally, the selected SiNP was attached to the probe tip with the assistance of the dark-field microscopic and spectroscopic system [cf. Fig. 2(f)]. The relative locations of the selected SiNP and the fiber tip can be visualized by this dark-field system in a real-time way. When the SiNP moves together with the fiber tip, the functional SiNP probe is successfully fabricated. The scanning electron microscopy (SEM) images of the bare fiber probe and the functional SiNP probe are illustrated in the upper and lower panels of Fig. 2(g), respectively. Detailed SEM images of the tips after each procedure are also presented in Appendix C.

To demonstrate the response of the proposed SiNP probe to the magnetic field vector of light, an imaging system with nanopolarimetry is needed. Here, nanopolarimetry means the
Fig. 2. (a) Dark-field spectrum of the selected silicon nanoparticle (SiNP). The inset shows a 100× blowup dark-field microscopic image of the measured SiNP. Scale bar, 500 nm. (b-f) Fabrication procedure of the functional SiNP probe. (g) SEM images of the fabricated probes: bare fiber probe (upper panel) and the functional probe with a SiNP (lower panel). Scale bars, 500 nm. (b) Schematics of the vectorial near-field microscope system. The nanoprobe converts the near fields into far fields and the Stokes parameters of the far-field light are analyzed by the vectorial near-field microscope. The rotating quarter-wave plate together with a stationary analyzer can continuously obtain the local Stokes parameters. The modulation of the chopper further increases the signal-to-noise ratio (SNR) of the system.

detection of polarization of light with subwavelength resolution. There are two typical methods to achieve the nanopolarimetry, one is the far-field detection by arrays of anisotropic plasmonic nanostructures [49,50] and the other is the near-field detection by a functional nanoprobe [15,16]. A home-built vectorial near-field microscope system [cf. Fig. 2(h) and Appendix D] is used to realize the functionality of probing the local vectors or Stokes parameters in near field, i.e., the nanopolarimetry [49,50]. The vectorial near-field microscope system can be roughly divided into two parts, the nanoprobe and the collection unit. The nanoprobe is precisely controlled by a shear-force mechanism and locally converts either the electric field or the magnetic field of light in near field to the propagating light in far field. Then the collection unit collects this far-field radiation and analyzes the Stokes parameter of the collected light. Finally, the near-field vector can be deduced from the measured Stokes parameter with deep subwavelength resolution. Thus, the nanoprobe senses the local electric or magnetic field of light at nanoscale while the collection unit achieves the polarimetry. The key feature of our system is that a rotating quarter-wave plate followed by a stationary polarizer [51] is incorporated to modulate the collected light. Compared with the systems with nanopolarimetry reported in [15,16], this technique can continuously probe the local Stokes parameters without multipole measurements for a single scanning point, neither by tens of rotations of a linear polarizer [15] nor by six operations of a combination set of a phase retarder and a linear polarizer [16]. Supposing that the Stokes parameter of the collected light is \( S = [S_0, S_1, S_2, S_3]^T \) and the rotating frequency of the quarter-wave plate is \( \omega \), the modulated intensity collected by the photomultiplier tube (PMT) casts in the form [51]

\[
I(t) = \frac{1}{2} S_0 + \frac{1}{4} S_1 - \frac{1}{2} S_3 \sin 2\omega t + \frac{1}{4} S_1 \cos 4\omega t + \frac{1}{4} S_2 \sin 4\omega t.
\] (3)

Equation (3) indicates that the detected signal is modulated by the local Stokes parameters. One can obtain the complete Stokes parameter simply by demodulation of a lock-in amplifier (LIA).
For further suppressing the direct current (DC) background noise of the PMT and the crosstalk noise with frequency 50 or 60 Hz [i.e., increasing the signal-to-noise ratio (SNR) of the system], we apply an optical chopper to shift the modulation frequency to a higher level. Supposing that the frequency of the chopper is $\Omega$, the detected signal $I_{\text{out}}(t)$ by amplitude modulation can be expressed as $I_{\text{out}}(t) = (1/2)[1 + \text{sgn}(\sin \Omega t)]I(t)$ where $\text{sgn}$ is the sign function. Thus, there are two sideband signals with frequencies $\Omega - 2\omega$ and $\Omega - 4\omega$, and these signals satisfy

$$
\begin{align*}
I_{\Omega-2\omega}(t) &= -\frac{1}{2\pi}S_3 \cos(\Omega - 2\omega)t \\
I_{\Omega-4\omega}(t) &= -\frac{1}{4\pi}S_2 \cos(\Omega - 4\omega)t + \frac{1}{4\pi}S_1 \sin(\Omega - 4\omega)t
\end{align*}
$$

Hence, one can get the circularly polarized component $S_3$ and the linearly polarized components $S_1$ and $S_2$ after demodulation with frequencies $\Omega - 2\omega$ and $\Omega - 4\omega$, respectively, and visualize the Stokes parameter with a associated polarization ellipse. Details on the demodulation method and the data processing are also presented in Appendix D.

2.3. Vectorial near-field imaging of the magnetic field vector of visible light

Two counter-propagating s-polarized surface waves generated by TIR inside a prism lead to a TE evanescent standing wave. As proof of the functionality of the nanopolarimetry and the fact that the fiber probe in the SiNP probe has no response to the magnetic field of light, a control experiment with the bare fiber probe [cf. the upper panel in Fig. 2(g)] is conducted. The vector field distribution of the TE evanescent standing wave in the $x-z$ plane at a wavelength of 532 nm has been measured by the bare fiber probe and visualized in Fig. 3. Figure 3(a) shows the vector field distribution (white double arrows, representing the major axis of the polarization ellipse) with sampling resolution $\Delta x = 20$ nm and $\Delta z = 40$ nm. Both the distribution of the major axis [cf. the upper panel in Fig. 3(a)] and that of the local polarization ellipses in one period of the evanescent standing wave at $z = 0$ nm [cf. the lower panel in Fig. 3(a)] indicate that a bare fiber tip is an effective sensor for the local electric field vector [43]. According to the local polarization ellipses, the electric field vector has been successfully visualized notwithstanding a minor deviation from the vertical linearly polarization. This deviation may originate from the imperfection and depolarization of the bare fiber tip.

Imperfections of the vector field system, especially the misalignment of the analyzer after the rotating quarter-wave plate, can generate measurement errors to the orientation angle $\Psi$ or the Stokes parameters $S_1$ and $S_2$ of the nanopolarimetry. Based on the fact that the bare fiber probe has little magnetic response and the scattered electric field of the TE evanescent standing wave is vertically polarized, we used the near-field measurements of $\Psi$ equipped with the bare fiber probe to calibrate the system and estimate the measurement error. After two near-field $x-z$ mappings with area $1.2 \times 0.32$ $\mu$m$^2$ and with sampling resolution $\Delta x = 10$ nm and $\Delta z = 20$ nm (i.e., $2 \times 120 \times 16 = 3840$ samples in total), the statistic of the relative errors in degree (i.e., $\Psi_E - 90^\circ$) is illustrated in Fig. 3(b). The blue curve shows a normal distribution of the statistic with a mean value of $\mu = 1.0^\circ$ and a standard deviation of $\sigma = 1.8^\circ$. Thus, we adjust the analyzer by rotating it $1.0^\circ$ clockwise, and set a conservative estimate of the measurement error as $3\sigma \approx 5.5^\circ$. Figure 3(c) presents the distribution of the orientation angle $\Psi_E$ of the measured vectors at $z = 0$ nm, also indicating that the vectors are around the vertical direction with $\pm 5.5^\circ$ tolerance and independent of the $x$ location. These results can also demonstrate the performance of the vectorial near-field microscope with nanopolarimetry and show that the electric field vector of visible light can be detected by a bare fiber probe.

For comparison, the vector field distribution of the TE evanescent standing wave has been measured by the fabricated SiNP probe [cf. the lower panel in Fig. 2(g)] and been visualized in Fig. 4. The experimental wavelength of the TE evanescent standing wave is 532 nm in...
Fig. 3. Mapping of the TE evanescent standing wave in near field by a bare fiber probe at a wavelength of 532 nm. (a) Electric field vector measurements: distribution of the amplitude and orientation (denoted by double arrows) for an $x-z$ area (720 nm $\times$ 280 nm) and distribution of polarization ellipse for one period along $x$-axis at $z = 0$ nm are displayed in the upper and lower panels, respectively. Backgrounds indicate the normalized measured electric intensities. Scale bars, 50 nm. (b) Statistics of the measured relative angles (3,840 samples) in degree (i.e., $\Psi_{E} - 90^o$) by the vectorial near-field microscopic system equipped with the bare fiber probe. (c) Orientation angles $\Psi_{E}$ of the electric field vectors at $z = 0$ nm. The red dashed line represents the theoretical values of the orientation angles. Inset shows the definition of the orientation angle $\Psi_{E}$.

Figs. 4(a) and (b) The thin white double arrows in the upper panel in Fig. 4(a) present the vector distributions directly obtained by the system with nanopolarimetry, while the thick black double arrows correspondingly represent the deduced field vector by an orthogonal operation (cf. details on the data processing in Appendix D). The thin and thick lines are used for visual guide. Remarkably, the orientation of the local near-field vector depends on the $x$ location and changes drastically along the $x$–axis. More specifically, the distribution of orientation angle $\Psi_{B}$ (i.e., orthogonal operation of $\Psi_{E}$) of the deduced vectors at $z = 0$ nm are illustrated in Fig. 4(b). The measured $\Psi_{B}$ (black squares) spans over the whole range $[-90^o, 90^o]$ for one period in $x$–direction, which are consistent with the theoretical values (red dashed line) generated by $B_x$ and $B_z$ in Eqs. (1). According to the analysis of Eq. (2), all the above results indicate that the functional SiNP probe is indeed an effective sensor for the magnetic field vector of light. To the best of our knowledge, it is for the first time that the magnetic field vector of light with ultrahigh frequency, whose frequency exceeds 550 THz, can be definitely detected and visualized in near field with the functional SiNP probe.

Compared with the functional probe with rare earth ions (e.g., Eu$^{3+}$) [29], one prevailing feature of the proposed SiNP probe is that it has a broader bandwidth with an effective magnetic response. For demonstrating the broadband feature of the SiNP, we use the same SiNP probe...
[cf. the lower panel in Fig. 2(g)] to measure the TE evanescent standing wave at a wavelength of 561 nm. Figure 4(c) shows the measured distribution of the orientation angles $\Psi_B$ at $z = 0$ nm. The consistency between Fig. 4(c) and Fig. 4(b) indicates that a conservative estimate of the bandwidth with an effective magnetic response of the SiNP probe is $\sim 30$ nm. For the dark-field spectrum in Fig. 2(a), the peak generated by the MD moment is around 580 nm. Thus, it is reasonable to conclude that the bandwidth with an effective magnetic response of the proposed SiNP probe is larger than 60 nm. For further covering the whole visible band, one can discretely selective SiNPs with different MD resonance wavelengths and fabricate the corresponding functional SiNP probes.

Fig. 4. Mapping of the TE evanescent standing wave in near field by a SiNP probe. (a) Magnetic field vector measurements at a wavelength of 532 nm: distribution of the amplitude and orientation (denoted by double arrows) for an $x - z$ area ($720 \text{ nm} \times 280 \text{ nm}$) and distribution of polarization ellipse for one period along $x$-axis at $z = 0$ nm are displayed in the upper and lower panels, respectively. White double arrows in (a) show the directly measured electric field vectors. Backgrounds indicate the normalized measured magnetic intensities. Scale bars, 50 nm. Orientation angles $\Psi_B$ of the magnetic field vectors at $z = 0$ nm at a wavelength of (b) 532 nm and (c) 561 nm. Red dashed lines represent the theoretical values of the orientation angles. Inset in (b) shows the definition of the orientation angle $\Psi_B$.

2.4. Interpretation of the near-field measurements of the magnetic field vector by reciprocity of electromagnetism

In theory, the magnetic field vector should be linear polarization in $x - z$ plane, whose distribution is illustrated in the upper row in Fig. 5. The theoretical polarization in one period is calculated by Eqs. (1) at $z = 0$ nm with wavelength 532 nm. The distribution of the measured polarization ellipses in the middle row in Fig. 5 is the same as that in the lower panel in Fig. 4(a), but with colored arrows indicating the helicity $\sigma$ of the corresponding polarization ellipse. According to Eq. (4), the helicity $\sigma$ of the magnetic polarization ellipses can be obtained by the sign of
S₃ as $\sigma = \text{sgn}(S_3)$ by our system with nanopolarimetry. By comparing between the middle and the upper rows in Fig. 5, the measured polarization ellipses well represent the near-field magnetic field vectors except for the deviation from the ideally linear polarization, which means that more circularly polarized light is detected by the SiNP probe. Interestingly, the measured magnetic field vectors not only become elliptic, but also have mirror helicities relative to the position where the measured polarization is almost linearly polarization (i.e., the singularities of the circularly polarized light). We contribute these phenomenon to the inherent ED moment generated in the SiNP [cf. Fig. 2(a)] and the ED moment of the supporting fiber tip. However, these phenomena cannot be quantitatively explained by the dipole radiation model expressed in Eq. (2) in a straightforward way. Thus, we apply reciprocity of electromagnetism to interpret the near-field measurement of the magnetic field vectors by the SiNP probe.

Reciprocity of electromagnetism can be used to describe the mechanism of SNOM [42,52,53] and reconstruct the near field of sample [35–37]. For a small tip, the near-field detection can be regarded as the coupling of a reciprocal electric dipole moment and the local electric field [53]. Recently, the magnetic coupling has been added to the electric one by introducing multipole expansion analysis to the reciprocal near-fields, and the detected far-field signal can be expressed as

$E_{\text{FF,pol}} \approx -p_{\text{tip,pol}} \cdot E_{\text{NF}} + m_{\text{tip,pol}} \cdot B_{\text{NF}}$

where $p_{\text{tip,pol}}$ and $m_{\text{tip,pol}}$ are the components of TE evanescent standing wave calculated by Eq. (1), and $\{m, p_{y,x}, \delta_{y,x}, p_{y,z}, \delta_{y,z}\}$ are real parameters. For each $x$ location, the far-field electric components can be explicitly expressed as

\[
\begin{align*}
E_{\text{FF},x}(x) &= -p_{y,x} \exp(i \delta_{y,x}) E_y(x) + m \cos(15^\circ) B_z(x) \\
E_{\text{FF},z}(x) &= -p_{y,z} \exp(i \delta_{y,z}) E_y(x) + m B_x(x),
\end{align*}
\]

(5)

where $B_x$, $E_y$, $B_z$ are the components of TE evanescent standing wave calculated by Eq. (1), and $\{m, p_{y,x}, \delta_{y,x}, p_{y,z}, \delta_{y,z}\}$ are real parameters. For each $x$ location, the far-field components $\{E_{\text{FF},x}, E_{\text{FF},z}\}$ can produce a polarization ellipse. Based on the measured polarization ellipses in the middle row in Fig. 5, the optimized parameters $\{m, p_{y,x}, \delta_{y,x}, p_{y,z}, \delta_{y,z}\} = \{c, 0.11, 31^\circ, 0.78, -111^\circ\}$ can be obtained by numerical fitting and optimization. The calculated polarization ellipses based on Eqs. (5) and the optimized parameters are illustrated in the lower row in Fig. 5, reproducing the deviation from the ideally linear polarization and the mirror helicities. In turn, the consistency between the measured and the calculated polarization ellipses also demonstrates the validity of the model based on reciprocity in Eqs. (5).
Reconsidering the optimized parameters, \( m \) is the magnitude of the induced MD moment governed by the SiNP, while \( \{p_{y,x}, \delta_{y,x}, p_{y,z}, \delta_{y,z}\} \) correspond to the ED moment contributed by both the fiber tip and the SiNP. Thus, the fitting and optimization process based on Eqs. (5) is actually a calibration process for the SiNP probe, which can determine the response of the SiNP probe to the external magnetic field of light. Reciprocity of electromagnetism provides a theoretical tool to quantitatively explain the differences between the measured magnetic field vector of light by the SiNP probe and the real magnetic near field. Besides, the calibration process can analyze and even reconstruct the responses of the SiNP probe to both the electric and the magnetic field vectors, which may lead towards the near-field measurement of the full vectors of light with deep subwavelength resolution.

3. Conclusion

To conclude, we have proposed and fabricated a novel functional nanoprobe that has a silicon nanoparticle on the tip of a fiber probe (i.e., the SiNP probe) to probe the magnetic field vector of light. As a proof-of-principle demonstration, the TE mode evanescent standing wave generated by total internal reflection has been measured in near field by the SiNP probe and a vector-resolved SNOM system with nanopolarimetry. To the best of our knowledge, it is for the first time that both the lateral and the vertical magnetic fields of light with ultrahigh frequency (exceeding 550 THz) have been simultaneously visualized with deep subwavelength resolution. Thus, the SiNP probe can probe the local magnetic field vector of light, complementary to the nanoprobe with a gold nanoparticle that senses the local electric field vector. The bottom-up fabrication technique of the SiNP probe may also accelerate the advance of novel functional probes with other high-index nanostructures for detection of the magnetic light, such as TiO\(_2\), GaAs, GaP, and InP, to name a few [40]. Here, the proposed SiNP probe and vector-resolved SNOM system with nano-polarimetry may open up the way for direct and complete 3D visualization of vectorial near-fields to a wealth of actively studied areas of nanophysics and nanomaterials, such as photonic topological insulators, photonic spin-orbit interactions, and all-dielectric metamaterials or metasurfaces, to name a few.

Appendix

A. Far-field radiation scattered by a nanoparticle probe

For the nanoparticle with almost spherical symmetry, the induced electric and magnetic dipole moments \( \{p, m\} \) are parallel to the local near-field electric and magnetic fields \( \{E, H\} \), respectively. Thus, for the probe-field system in Fig. 1(a), the induced dipole moments can be expressed as \( p = (0, -p, 0)^T \) and \( m = (m \cos \Psi, 0, m \sin \Psi)^T \) where \( p \) and \( m \) are the magnitude of \( p \), the magnitude of \( m \) and the orientation angle between \( m \) and \( x \)-axis. According to the far-field radiation expressions of dipole moments [i.e., \( E_p \propto r^{-1}(n \times p) \times n \) and \( E_m \propto -r^{-1}(n \times c^{-1} m) \)] [54], one can obtain the total electric field scattered by a nanoparticle probe

\[
E = E_p + E_m \propto \begin{pmatrix} 0 \\ -p \sin^2 \theta \\ p \sin \theta \cos \theta \end{pmatrix} - r^{-1}\begin{pmatrix} m \sin \Psi \cos \theta \\ m \cos \Psi \sin \theta \\ -m \cos \Psi \cos \theta \end{pmatrix},
\]

where \( \theta \) is the pitch angle relative to the \( y \)-axis and the associated normal vector is \( n = (0, \cos \theta, \sin \theta)^T \). Equation (6) describes the electric field in the \( xyz \) coordinate, and can be
linearly transferred into the $xy'z'$ coordinate as

$$
E' = E'_p + E'_m \propto \begin{pmatrix}
0 & m \sin \Psi \cos \theta \\
0 & -c^{-1} \\
p \sin \theta & 0 \\
0 & -m \cos \Psi
\end{pmatrix}
$$

with superscript $'$ denoting the fields in the $xy'z'$ coordinate. Thus, for a small pitch angle (i.e., $\theta \leq 30^\circ$), Eq. (2) is derived by a further simplification of Eq. (7) by taking $\sin(\theta) \approx \theta$ and $\cos(\theta) \approx 1 - (1/2)\theta^2$.

**B. Fabrication and selection of the silicon nanoparticles**

SiNPs with smooth surfaces were fabricated by the laser ablation method [44]. Focused femtosecond laser (Legend Elite F-HE, Coherent Co.) with pulse duration of 35 fs and energy-per-pulse 4 mJ illuminated a silicon wafer in the deionized (DI) water. After 10 minutes of laser ablation, we were able to obtain silicon colloid, which contained SiNPs with diameters from 60 to 200 nm, suspended in the DI water. Then, a few drops of the solution with volume 2 $\mu$L were separately transferred to a clean cover glass (NEO, Matsunami Co.). During evaporation, SiNPs were distributed well on the cover glass though with aggregation resulted from capillary forces. SiNPs with desired diameters or resonance wavelength can be selected by a home-built dark-field microscopic and spectroscopic system. This system is mainly developed by a commercial optical microscope (IX81, Olympus Co.). The dark-field scheme is fulfilled by a combination of a dark-field module (U-MDF3, Olympus Co.) and a $100 \times/0.9$ dark-field objective (MPLFLN100XBD, Olympus Co.). For dark-field spectroscopy, the microscope is connected with a spectrometer (inVia, Renishaw Co.), which uses a 300 l/mm grating. The thin cover glass, which carries nanoparticles on its upper surface, is mounted on and controlled by a three dimensional (3D) motorized translation stage (9063-XYX-PPP, Newport Co.). The translation stage can move the nanoparticles with resolution tens of nanometers. With the assistance of a digital camera (DS-Fi2, Nikon Co.), the well-separated nanoparticle with desired scattering color can be selected.

For obtaining the dark-field scattering spectrum of the nanoparticle, four spectrums should be measured. First, the spectrum of the system noise is measured by removing the cover glass, which is denoted as $I_{\text{noise}}(\omega)$. Second, the spectrum of the source, i.e., a halogen lamp in our system, is measured by reflection of a diffuse reflectance standard (Labsphere Inc.), which is denoted as $I_{\text{source}}(\omega)$. Third, the spectrum of the selected nanoparticle is measured, which is denoted as $I_{\text{signal}}(\omega)$. Fourth, the spectrum of the background generated by the cover glass is measured by shifting the selected nanoparticle out of the detection area, which is denoted as $I_{\text{background}}(\omega)$. Thus, the dark-field spectrum of the selected nanoparticle $I(\omega)$ can be expressed as

$$
I(\omega) = \frac{I_{\text{signal}}(\omega) - I_{\text{background}}(\omega)}{I_{\text{source}}(\omega) - I_{\text{noise}}(\omega)}.
$$

**C. Visualization of the functional probes and fabrication of the parabolic fiber probes**

Figure 6 illustrates the scanning electron microscopic (SEM) images of the probes at different procedures where Figs. 6(a) and 6(b), Fig. 6(c), and Figs. 6(d), 6(e) and 6(f) are taken by Hitachi SU8220, Hitachi S-4800, and FEI QUANTA 200 FEG, respectively. Figures 6(a) and 6(b) are the original SEM images of the applied bare fiber probe and SiNP probe in Fig. 2(g).

The parabolic fiber probes were produced with a two-step procedure as follows [55,56]. First, a bare fiber probe was prepared by the heating-pulling method on a commercial laser-based puller (P-2000/F, Sutter Instrument Co.) with optimized parameters of the instrument: Heat = 190, Filament = 0, Velocity = 20, Delay = 126 and Pull = 150. The performed probe
owned a well-defined transitional parabolic profile and had a tenuously filament tip with tens of micrometers length and \( \sim 6 \mu m \) diameter, as shown in Fig. 6(c). Second, the parabolic probe was subsequently processed by etching to further shorten the overall taper length. A segment of the probe with length 2 mm was immersed into the 40\% hydrofluoric acid (HF) covered by an organic layer for protection. During the etching process, the room temperature was kept at 15 \(^\circ\)C. Finally, the parabolic fiber tips with curvature radius \( \sim 60 \) nm and different cone angles could be achieved by controlling the etching time. As illustrated in Figs. 6(d) and 6(f), the fiber tips have a cone angle of \( \sim 30^\circ \) and \( \sim 60^\circ \) with etching time \( \sim 5 \) and \( \sim 7 \) minutes, respectively. Compared with the one-step heating-pulling method, this method can produce parabolic probes with shorter taper lengths leading to a lower damage probability when the probes approach the sample surface.

Before immersed into the solution containing the chemical crosslinker (e.g., APTES), the fiber tip should be made clean and hydrophilic to enhance the adhesion between the tip and the crosslinker. Figure 6(f) shows a SEM image of one fiber tip without clean and hydrophilic treatment where the thin APTES layer falls off, obviously indicating the necessity of the corresponding procedure in Fig. 2(d).

**D. Vectorial near-field microscope with nanopolarimetry and demodulation method**

The vectorial near-field microscope in Fig. 2(h) has mainly two parts: a near-field microscope and a far-field microscope. The near-field microscope was developed based on a commercial SNOM system (SNLG112NTF, NT-MDT Co.), where a probe approaches the surface of the sample and scatters the near field to the far field. The illumination light was modulated by an optical chopper (SR540, Stanford Research Systems) with frequency \( \Omega = 2\pi \times 3 \) kHz. As for the far-field microscope, a video microscope unit (VMU, Mitutoyo Co.) equipped with a long working distance objective (20 \( \times / 0.29 \) Plan Apo, Mitutoyo Co.) was used to image the tip-sample system and collect the scattering light. This unit was mounted on an articulating platform (AP180, Thorlabs Co.) to keep the pitch angle \( \theta = 15^\circ \) between the optic axis and
the y–axis. Two orthogonal adjustable slits (VA100/M, Thorlabs Co.) were located at the imaging planes of the far-field microscope to limit the imaging area with dimensions around 5 µm × 5 µm. For simplicity, Fig. 2(h) only illustrates one variable slit. Then, the scattering light was modulated by a rotating quarter-wave plate and a stationary polarizer (LPVIS050, Thorlabs Co.) where the quarter-wave plate (AQWP05M-600, Thorlabs Co.) was mounted on a hollow shaft motor (HMS604 E18H, Technohands Co.) with speed ~1300 r.p.m. (i.e., ω ≈ 2π × 22 Hz). Finally, the focused scattering light was collected by a photomultiplier tube (PMT) (H5784-20, Hamamatsu Co.). After demodulation of the converted signal by a digital lock-in amplifier (LIA) (HF2LI, Zurich Instruments), the local Stokes parameter of the linear components S1 and S2 and that of the circular component S3 can be simultaneously obtained according to Eq. (4).

Supposing that the normalized cosine reference signals in LIA are

\[
\begin{align*}
I_{\text{ref},2}(t) &= \cos [(\Omega - 2\omega)t + \phi_1] \\
I_{\text{ref},4}(t) &= \cos [(\Omega - 4\omega)t + \phi_2]
\end{align*}
\]  

(9)

where φ1 and φ2 two relative phases of the system should be calibrated as follows. First, using the vectorial near-field microscopic system to measure a standard right circularly polarized plane wave, i.e., S = [1, 0, 1]T, and let x_{Ω−2ω} and y_{Ω−2ω} denote the output signals with frequency Ω − 2ω of LIA. Second, using the vectorial near-field microscopic system to measure a standard right circularly polarized plane wave, i.e., S = [1, 0, 1]T, and let x_{Ω−4ω} and y_{Ω−4ω} denote the output signals with frequency Ω − 4ω of LIA. Thus, the two relative phases can be expressed as

\[
\begin{align*}
\bar{\phi}_2 &= \text{sgn}(y_{Ω−4ω}) \arccos \frac{x_{Ω−4ω}}{\sqrt{x_{Ω−4ω}^2 + y_{Ω−4ω}^2}} \\
\bar{\phi}_1 &= \text{sgn}(y_{Ω−2ω}) \arccos \frac{x_{Ω−2ω}}{\sqrt{x_{Ω−2ω}^2 + y_{Ω−2ω}^2}}
\end{align*}
\]  

(11)

According to Eq. (10) and the calibrated relative phases of the system \(\bar{\phi}_1\) and \(\bar{\phi}_2\), one can obtain the demodulated Stokes parameter

\[
\begin{align*}
S_1 &= -8\pi (x_{Ω−4ω} \sin \bar{\phi}_2 - y_{Ω−4ω} \cos \bar{\phi}_2) \\
S_2 &= 8\pi (x_{Ω−4ω} \cos \bar{\phi}_2 + y_{Ω−4ω} \sin \bar{\phi}_2) \\
S_3 &= -4\pi (x_{Ω−2ω} \cos \bar{\phi}_1 + y_{Ω−2ω} \sin \bar{\phi}_1) \\
S_0 &= \sqrt{S_1^2 + S_2^2 + S_3^2}
\end{align*}
\]  

(12)

In summary, there are totally six steps for the measurement of the local vector or Stokes parameter and the procedure of the data processing for each scanning point of the nanoprobe.
First, the system with nanopolarimetry is calibrated by a +45° linearly polarized light and right circularly polarized light to obtain the system parameters $\tilde{\phi}_1$ and $\tilde{\phi}_2$ according to Eq. (11). Second, the nanoprobe locally converts either the electric field or the magnetic field of the light to be measured to the far field. Third, the scattered light is collected by the system and is simultaneously modulated by the optical chopper and the rotating quarter-wave plate followed by the stationary polarizer. Fourth, the modulated light is in the form of Eq. (4) and is collected by the detector, e.g., PMT. Fifth, the Stokes parameter of the scattered light can be obtained after demodulation by a LIA according to Eq. (12), denoted by $S_{FF} = [S_0, S_1, S_2, S_3]^T$. Last, for a nanoprobe with good spherical symmetry, the corresponding local Stokes parameter $S_{NF}$ satisfies either $S_{NF} \propto [S_0, S_1, S_2, S_3]^T$ for an electric-sensitive probe (e.g., the GNP) or $S_{NF} \propto [S_0, -S_1, -S_2, S_3]^T$ for a magnetic-sensitive probe (e.g., the SiNP). For any Stokes parameter $S = [S_0, S_1, S_2, S_3]^T$, there is a corresponding polarization ellipse represented by an orientation angle $\psi$ and an ellipticity angle $\chi$. Equations (13) and (14) show the transformation relation between the polarization ellipse and the Stokes parameter.

$$\chi = \frac{1}{2} \arcsin \frac{S_3}{S_0}$$  \hspace{1cm} (13)

$$\psi = \begin{cases} 
\frac{1}{2} \arcsin \frac{S_2}{S_0 \cos 2\chi}, & \text{for } S_1 > 0, S_2 > 0 \\
\frac{1}{2} \arccos \frac{S_1}{S_0 \cos 2\chi}, & \text{for } S_1 < 0, S_2 > 0 \\
\pi - \frac{1}{2} \arccos \frac{S_1}{S_0 \cos 2\chi}, & \text{for } S_1 < 0, S_2 < 0 \\
\pi + \frac{1}{2} \arcsin \frac{S_2}{S_0 \cos 2\chi}, & \text{for } S_1 > 0, S_2 < 0
\end{cases}$$  \hspace{1cm} (14)

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