

Article

Superchiral-Field-Enhanced Photoinduced Force Microscopy for Nanoscale Chiral Characterization via Magnetic-Dipole Excitation

Xu Wang and Guanghao Rui *

Department of Optical Engineering, School of Electronic Science and Engineering, Southeast University, Nanjing 211189, China; 213232587@seu.edu.cn

* Correspondence: ghrui@seu.edu.cn

Abstract

The chiral interaction between light and matter is intrinsically weak at the nanoscale, which leads to a sensitivity bottleneck in the detection of chiral samples by photoinduced force microscopy. To address this issue, we propose an enhancement strategy that combines a semiconductor tip with a superchiral optical field to improve the optical force response in nanoscale chiral detection. Compared with a conventional metallic tip, a silicon tip can generate a larger optical force difference under left- and right-handed circularly polarized illumination. This enhancement mainly arises from the more pronounced magnetic response of the silicon tip, which increases the contribution of the magnetic dipole term to the total optical force. Furthermore, when the incident field is changed from a circularly polarized field to a superchiral field, the optical force difference acting on the same tip can be further increased by more than one order of magnitude. Relative to the reference case of a gold tip excited by circularly polarized light, the combination of a superchiral field and a silicon tip enhances the optical force difference by nearly two orders of magnitude. Analysis based on the dipole approximation shows that this enhancement originates from the synergistic effect of two factors: the high-refractive-index silicon tip provides a stronger magnetic response, while the superchiral field further strengthens the coupling between the localized chiral field and the tip and effectively excites the magnetic dipole and electromagnetic coupling terms, thereby jointly amplifying the chiral optical force signal. This work provides a new route for the highly sensitive detection of chiral materials at the nanoscale and may further extend the applications of photoinduced force microscopy in the characterization of chirality and optomagnetic interactions.

Keywords: photoinduced force microscopy; superchiral optical field; semiconductor tip; chiral characterization; optical force effect

Received: 3 July 2026

Revised: 30 July 2026

Accepted: 30 July 2026

Published: 31 July 2026

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1. Introduction

Chirality is a fundamental property of molecules or materials arising from the lack of mirror symmetry in their spatial structure. Owing to this structural feature, a chiral object cannot be superimposed onto its mirror image through translation or rotation [1]. Molecules with opposite chirality often exhibit distinct physicochemical properties. For example, different enantiomers of a chiral drug may produce different pharmacological or toxic effects in biological systems. Therefore, given the importance of chirality in fields

such as biomedicine and chemical engineering, the detection and characterization of chiral enantiomers have become critical issues [2]. To address this problem, early studies proposed spectroscopic techniques based on Raman optical activity, optical rotatory dispersion, and circular dichroism [3–6]. These methods mainly utilize the differential responses of chiral substances to left- and right-handed circularly polarized light, so as to acquire information related to the chiral parameters and structures of samples [7–9]. However, especially for circular dichroism detection, the measured results essentially reflect the far-field average response, and thus the localized information carried in the near field is usually neglected. Moreover, the interaction between light and chiral nanoparticles is typically weak at the nanoscale, causing chiral spectroscopic detection to generally suffer from insufficient sensitivity. To enhance the interaction between light and chiral matter, researchers introduced the concept of superchiral optical fields. Compared with conventional circularly polarized light, superchiral optical fields possess a higher optical chirality density and can excite the circular dichroic response of chiral molecules more effectively, thereby improving detection sensitivity [10]. In recent years, researchers have generated superchiral light fields through multiple approaches, including the plasmonic–photonic cavity mode interaction [11], the interference of two counter-propagating circularly polarized lights [1,12], and the focusing of radially polarized vortex beams on glass substrates [13]. Accordingly, leveraging the enhancement effect of superchiral light fields on chiral optical responses offers a new route to developing high-sensitivity chiral detection technologies at the nanoscale.

The optical force effect arising from light–matter interactions has been widely applied in biomedicine, physics, and chemistry [14–21]. Optical forces can not only drive particles to move forward or backward, but also enable particle trapping and the separation of chiral particles [22–28]. When the achiral optical force acting on a chiral particle is suppressed, the chiral optical force can drive particles of opposite handedness to move in opposite directions. When the achiral optical force on chiral particles is suppressed, the chiral optical force can drive particles of opposite handedness in opposite directions. Using this mechanism, researchers have separated chiral nano- and microparticles by lateral optical forces in interference fields, structured focal fields, and evanescent waves [29–31]. However, such sorting methods based on the optical force effect mainly distinguish the chirality of particles relying on their motion trajectories, which makes high-resolution characterization and quantitative analysis of nanoscale chiral structures difficult to achieve.

Light-induced force microscopy leverages an optical field to excite the probe–sample coupled system, enabling the measurement of local optical properties of samples with the high spatial resolution afforded by atomic force microscopy [32–35]. A commonly used probe consists of a silicon-based cantilever with a metallic coating, such as gold or PtIr, deposited on its tip. By integrating structured optical fields with the photo-induced force microscopy platform, structured-light-induced force microscopy can be realized in the coupled tip–sample system [36,37], thereby further enhancing its ability to probe complex near-field components. By leveraging the near-field information generated from the probe–sample interaction with the optical field, this technique bypasses the conventional far-field diffraction limit, granting it unique advantages in localized optical characterization. Among them, Zeng et al. realized the direct detection of nanoscale optically induced magnetic forces by employing structured light-induced force microscopy, and revealed the magnetic near-field effect of structured light [38]. Based on the above technique, researchers have achieved the characterization of various chiral samples. When using ordinary circularly polarized light for excitation, the detection of isotropic chiral nanosamples can be accomplished. When using a directional chiral dipole focal field for excitation, spatially resolved characterization of anisotropic chiral structures can be performed [39,40]. Although photo-induced force microscopy has shown clear advantages for chiral

characterization, the sensitivity of optical force detection in existing metal-probe systems still requires further improvement and remains insufficient for nanoscale characterization of ultra-trace, weak chiral signals.

On this basis, this study proposes a photo-induced force microscopy approach that combines a semiconductor probe with a superchiral optical field for enantiomer detection in chiral samples at the nanoscale, and demonstrates significantly enhanced differential optical force detection in a silicon tip-sample system. Previous chiral PiFM studies have demonstrated the retrieval of sample handedness or chirality parameters using conventional probes and circularly polarized or structured optical fields. Meanwhile, optomagnetic PiFM has enabled the detection of magnetic near fields, and superchiral optical fields have enhanced conventional chiroptical signals. However, the coordinated use of a magnetic-dipole-responsive probe and a localized superchiral field to enhance the chirality-dependent photoinduced force has not been systematically investigated. In this work, a Si probe operated near its magnetic-dipole resonance is combined with a localized superchiral optical field. The differential force is decomposed into electric, magnetic, and electric-magnetic coupling contributions to identify the physical origin of the enhancement. The combined probe-field configuration provides an approximately 140-fold enhancement relative to the Au-probe/CPL reference under equal total incident power. Under equal local electric-field amplitude and using the same Si probe, the superchiral excitation retains an approximately 20-fold enhancement over CPL. At high-resolution scales, this scheme is predicted to reduce the minimum detectable chiral parameter of the sample by two orders of magnitude, significantly improving the detection sensitivity. The main reason lies in the fact that the superchiral optical field more effectively excites the magnetic dipole term and the electromagnetic coupling term in the silicon probe. The results presented in this work contribute to the effective characterization of nanoscale chirality and deepen the understanding of the mechanisms underlying light-matter interactions.

2. Theoretical Model

Figure 1a shows a schematic diagram of the structured light-induced force microscope model adopted in this work. In this model, the incident light propagates from the bottom of the tip-sample system along the z-direction, and excites electromagnetic responses in both the tip and the sample, thereby inducing secondary scattering. In photo-induced force microscopy, the electromagnetic field around the probe and the sample is redistributed, and their near-field scattering interaction induces a pronounced longitudinal optical force on the probe. This work aims to enhance the difference in the longitudinal optical force under different chiral excitation conditions by tailoring the probe material and the incident field, thereby further improving the capability of photo-induced force microscopy for detecting nanoscale chiral samples. To reveal the fundamental physical mechanism of this light-induced force microscope in nanoscale chiral detection, both the sample and the probe tip are simplified as isotropic spherical nanoparticles with sizes much smaller than the incident wavelength, as shown in Figure 1b. Based on the dipole approximation, the time-averaged optical force acting on the probe can be expressed as [41]:

$$\mathbf{F} = \frac{1}{2} \text{Re} \left[\left(\nabla \mathbf{E}^{loc}(\mathbf{r}_t)^* \cdot \mathbf{p}_t + (\nabla \mathbf{H}^{loc}(\mathbf{r}_t)^* \cdot \mathbf{m}_t - \frac{ck^4}{6\pi} (\mathbf{p}_t \times \mathbf{m}_t)^* \right) \right] \quad (1)$$

Here, $\mathbf{p}_t$ and $\mathbf{m}_t$ represent the electric dipole moment and magnetic dipole moment at the probe, respectively, and are defined as follows [39]:

$$\begin{cases} \mathbf{p}_t = \alpha_t^{ee} \cdot \mathbf{E}^{loc}(\mathbf{r}_t) \\ \mathbf{m}_t = \alpha_t^{mm} \cdot \mathbf{H}^{loc}(\mathbf{r}_t) \end{cases} \quad (2)$$

α_t^{ee} and α_t^{mm} denote the electric and magnetic polarizabilities of the probe, respectively. $\mathbf{E}^{loc}(\mathbf{r}_t)$ and $\mathbf{H}^{loc}(\mathbf{r}_t)$ represent the local electric and magnetic fields at the probe apex position $\mathbf{r}_t$, respectively, and can be written as [38–40]:

$$\begin{cases} \mathbf{E}^{loc}(\mathbf{r}_t) = \mathbf{E}^{inc}(\mathbf{r}_t) + \mathbf{E}_{scat}|_{s \rightarrow t} = \mathbf{E}^{inc}(\mathbf{r}_t) + \mathbf{G}^{EE}(\mathbf{r}_t, \mathbf{r}_s) \cdot \mathbf{p}_s + \mathbf{G}^{EM}(\mathbf{r}_t, \mathbf{r}_s) \cdot \mathbf{m}_s \\ \mathbf{H}^{loc}(\mathbf{r}_t) = \mathbf{H}^{inc}(\mathbf{r}_t) + \mathbf{H}_{scat}|_{s \rightarrow t} = \mathbf{H}^{inc}(\mathbf{r}_t) + \mathbf{G}^{ME}(\mathbf{r}_t, \mathbf{r}_s) \cdot \mathbf{p}_s + \mathbf{G}^{MM}(\mathbf{r}_t, \mathbf{r}_s) \cdot \mathbf{m}_s \end{cases} \quad (3)$$

Here, $\mathbf{E}_{scat}|_{s \rightarrow t}$ and $\mathbf{H}_{scat}|_{s \rightarrow t}$ represent the electric field and magnetic field scattered from the sample to the probe tip position, respectively. $\mathbf{E}^{inc}(\mathbf{r}_t)$ and $\mathbf{H}^{inc}(\mathbf{r}_t)$ are the incident electric field and magnetic field at the tip position $\mathbf{r}_t$, respectively. Equation (3) explicitly gives the field scattered from the sample to the tip. However, this term is part of the coupled local-field formulation rather than an isolated one-way scattering treatment. The induced electric and magnetic dipole moments of the tip and sample are coupled through the local-field equations, so that their mutual interaction is retained at the dipolar level. For the 10 nm-gap configuration, this treatment includes the dominant dipolar near-field coupling but does not fully account for finite-size, retardation, and higher-order multipolar effects. $\mathbf{G}^{EE}(\mathbf{G}^{EM})$ and $\mathbf{G}^{ME}(\mathbf{G}^{MM})$ are the scalar Green's functions in the free-space Green's function formulation, representing the electric and magnetic fields induced by the electric dipole $\mathbf{p}_s$ (magnetic dipole $\mathbf{m}_s$), respectively. Their specific forms are given as:

$$\mathbf{G}^{EE} = \frac{1}{\epsilon_0} (k_0^2 \bar{\mathbf{I}} + \nabla \nabla) \mathbf{G} \quad (4)$$

$$\mathbf{G}^{EM} = i\omega (\nabla \mathbf{G} \times \bar{\mathbf{I}}), \quad (5)$$

$$\mathbf{G}^{ME} = -i\omega \frac{1}{\mu_0} (\nabla \mathbf{G} \times \bar{\mathbf{I}}), \quad (6)$$

$$\mathbf{G}^{MM} = \frac{1}{\mu_0} (k_0^2 \bar{\mathbf{I}} + \nabla \nabla) \mathbf{G}, \quad (7)$$

the Green's function is given by $\mathbf{G} = \exp[ik_0(\mathbf{r} - \mathbf{r}_0)/4\pi(\mathbf{r} - \mathbf{r}_0)]$, where k_0 is the wave vector in free space, $\bar{\mathbf{I}}$ is the unit tensor, $\mathbf{r}$ and $\mathbf{r}_0$ represent the tip position and the sample position, respectively. The scattered electromagnetic field from the sample to the tip can be expressed as:

$$\begin{cases} \mathbf{E}_{scat}|_{s \rightarrow t} = -\frac{G_0}{\epsilon_0} (p_{s,x}\hat{x} + p_{s,y}\hat{y} - 2p_{s,z}\hat{z}) \\ \mathbf{H}_{scat}|_{s \rightarrow t} = -\frac{G_0}{\mu_0} (m_{s,x}\hat{x} + m_{s,y}\hat{y} - 2m_{s,z}\hat{z}) \end{cases} \quad (8)$$

Here, $G_0 = \exp(ik_0|\mathbf{z}_t - \mathbf{z}_s|)/4\pi|\mathbf{z}_t - \mathbf{z}_s|^3$, where $\mathbf{z}_t$ and $\mathbf{z}_s$ denote the positions of the tip and the sample, respectively. Assuming that the sample is composed of an isotropic chiral material, $\mathbf{p}_s$ and $\mathbf{m}_s$ can be described in terms of the polarizabilities and the local fields as [42]:

$$\begin{bmatrix} \mathbf{p}_s \\ \mathbf{m}_s \end{bmatrix} = \begin{bmatrix} \alpha_s^{ee} & i\alpha_s^{em} \\ -i\alpha_s^{em} & \alpha_s^{mm} \end{bmatrix} \begin{bmatrix} \mathbf{E}^{loc}(\mathbf{r}_s) \\ \mathbf{H}^{loc}(\mathbf{r}_s) \end{bmatrix} \quad (9)$$

Here, $\mathbf{E}^{loc}(\mathbf{r}_s)$ and $\mathbf{H}^{loc}(\mathbf{r}_s)$ represent the local electric field and magnetic field acting at the sample position $\mathbf{r}_s$, respectively. The electric polarizability α_s^{ee} , magnetic polarizability α_s^{mm} , and electromagnetic polarizability α_s^{em} can be expressed as follows [43]:

$$\alpha_s^{ee} = \frac{i6\pi\epsilon_s\epsilon_0}{k_1^3} a_{1,s}, \alpha_t^{ee} = \frac{i6\pi\epsilon_t\epsilon_0}{k_1^3} a_{1,t}, \alpha_s^{mm} = \frac{i6\pi\mu_s\mu_0}{k_1^3} b_{1,s}, \alpha_t^{mm} = \frac{i6\pi\mu_t\mu_0}{k_1^3} b_{1,t} \quad (10)$$

$$\alpha_s^{em} = \frac{6\pi n_1}{ck_1^3} c_{1,s}$$

The superscripts s and t denote the chiral sample and the probe tip, respectively. The electric, magnetic, and magnetoelectric polarizabilities of the sample are calculated from its first-order Mie coefficients $a_{1,s}$, $b_{1,s}$, and $c_{1,s}$ [44]. The electric and magnetic polarizabilities of the achiral probe are calculated independently from $a_{1,t}$ and $b_{1,t}$, while $c_{1,t} = 0$ and consequently $\alpha_t^{em} = 0$. The sample and probe therefore have different Mie coefficients and polarizabilities because they are described by different constitutive parameters. $k_1 = n_1\omega/c$ is the wavenumber, where ω is the angular frequency of light, ϵ_1 and μ_1 are the relative permittivity and relative permeability of the background medium, respectively, and $n_1 = (\epsilon_1\mu_1)^{1/2}$ is the refractive index of the medium.

Substituting Equation (9) into Equation (3), the expressions for the local electric field and magnetic field near the probe tip can be obtained as:

$$\begin{bmatrix} E_x^{loc}(x_t) \\ E_y^{loc}(x_t) \\ E_z^{loc}(x_t) \end{bmatrix} = \begin{bmatrix} E_x^{inc}(x_t) \\ E_y^{inc}(x_t) \\ E_z^{inc}(x_t) \end{bmatrix} - \frac{G_0}{\epsilon_0} \begin{bmatrix} \alpha_s^{ee} E_x^{loc}(x_s) + i\alpha_{s,xx}^{em} H_x^{loc}(x_s) \\ \alpha_s^{ee} E_y^{loc}(x_s) + i\alpha_{s,yy}^{em} H_y^{loc}(x_s) \\ -2\alpha_s^{ee} E_z^{loc}(x_s) - 2i\alpha_{s,zz}^{em} H_z^{loc}(x_s) \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} H_x^{loc}(x_t) \\ H_y^{loc}(x_t) \\ H_z^{loc}(x_t) \end{bmatrix} = \begin{bmatrix} H_x^{inc}(x_t) \\ H_y^{inc}(x_t) \\ H_z^{inc}(x_t) \end{bmatrix} - \frac{G_0}{\mu_0} \begin{bmatrix} -i\alpha_{s,xx}^{em} E_x^{loc}(x_s) + \alpha_s^{mm} H_x^{loc}(x_s) \\ -i\alpha_{s,yy}^{em} E_y^{loc}(x_s) + \alpha_s^{mm} H_y^{loc}(x_s) \\ 2i\alpha_{s,zz}^{em} E_z^{loc}(x_s) - 2\alpha_s^{mm} H_z^{loc}(x_s) \end{bmatrix} \quad (12)$$

Because the circularly polarized optical field has no z-component, the local field distribution near the tip can be obtained from Equations (11) and (12) as follows:

$$\begin{bmatrix} E_x^{loc}(z_t) \\ E_y^{loc}(z_t) \end{bmatrix} = \begin{bmatrix} E_x^{inc}(z_t) \\ E_y^{inc}(z_t) \end{bmatrix} - \frac{G_0}{\epsilon_0} \begin{bmatrix} \alpha_s^{ee} (E_x^{inc}(z_t) - \frac{G_0}{\epsilon_0} \alpha_t^{ee} E_x^{loc}(z_t)) + i\alpha_s^{em} (H_x^{inc}(z_t) - \frac{G_0}{\mu_0} \alpha_t^{mm} H_x^{loc}(z_t)) \\ \alpha_s^{ee} (E_y^{inc}(z_t) - \frac{G_0}{\epsilon_0} \alpha_t^{ee} E_y^{loc}(z_t)) + i\alpha_s^{em} (H_y^{inc}(z_t) - \frac{G_0}{\mu_0} \alpha_t^{mm} H_y^{loc}(z_t)) \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} H_x^{loc}(z_t) \\ H_y^{loc}(z_t) \end{bmatrix} = \begin{bmatrix} H_x^{inc}(z_t) \\ H_y^{inc}(z_t) \end{bmatrix} - \frac{G_0}{\mu_0} \begin{bmatrix} -i\alpha_s^{em} (E_x^{inc}(z_t) - \frac{G_0}{\epsilon_0} \alpha_t^{ee} E_x^{loc}(z_t)) + \alpha_s^{mm} (H_x^{inc}(z_t) - \frac{G_0}{\mu_0} \alpha_t^{mm} H_x^{loc}(z_t)) \\ -i\alpha_s^{em} (E_y^{inc}(z_t) - \frac{G_0}{\epsilon_0} \alpha_t^{ee} E_y^{loc}(z_t)) + \alpha_s^{mm} (H_y^{inc}(z_t) - \frac{G_0}{\mu_0} \alpha_t^{mm} H_y^{loc}(z_t)) \end{bmatrix} \quad (14)$$

By combining Equations (13) and (14), the local field near the tip can be obtained. Owing to the symmetry between the x and y components, only the x component is presented below.

$$\begin{cases} E_x^{loc} = \frac{\epsilon_0(\alpha_1 G_0^3 + \alpha_2 G_0^2 + \alpha_3 G_0 + E_x^{inc} \mu_0^2 \epsilon_0)}{T} \\ \alpha_1 = E_x^{inc} \alpha_t^{mm} [-(\alpha_s^{em})^2 + \alpha_s^{ee} \alpha_s^{mm}] \\ \alpha_2 = \alpha_t^{mm} (-E_x^{inc} \alpha_s^{mm} \epsilon_0 + iH_x^{inc} \mu_0 \alpha_s^{em}) \\ \alpha_3 = -\mu_0^2 (iH_x^{inc} \alpha_s^{em} + E_x^{inc} \alpha_s^{ee}) \\ T = \alpha_t^{ee} \alpha_t^{mm} [-(\alpha_s^{em})^2 + \alpha_s^{ee} \alpha_s^{mm}] G_0^4 + (-\alpha_s^{mm} \alpha_t^{mm} \epsilon_0^2 - \mu_0^2 \alpha_s^{ee} \alpha_t^{ee}) G_0^2 + \mu_0^2 \epsilon_0^2 \end{cases} \quad (15)$$

$$\begin{cases} H_x^{loc} = \frac{\mu_0(\beta_1 G_0^3 - \beta_2 G_0^2 + \beta_3 G_0 + H_x^{inc} \mu_0 \varepsilon_0^2)}{T} \\ \beta_1 = H_x^{inc} \alpha_t^{ee} [-(\alpha_s^{em})^2 + \alpha_s^{ee} \alpha_s^{mm}] \\ \beta_2 = \alpha_t^{ee} (i E_x^{inc} \alpha_s^{em} \varepsilon_0 + H_x^{inc} \alpha_s^{ee}) \\ \beta_3 = \varepsilon^2 (i E_x^{inc} \alpha_s^{em} - \alpha_s^{mm} H_x^{inc}) \\ T = \alpha_t^{ee} \alpha_t^{mm} [-(\alpha_s^{em})^2 + \alpha_s^{ee} \alpha_s^{mm}] G_0^4 + (-\alpha_s^{mm} \alpha_t^{mm} \varepsilon_0^2 - \mu_0^2 \alpha_s^{ee} \alpha_t^{ee}) G_0^2 + \mu_0^2 \varepsilon_0^2 \end{cases} \quad (16)$$

Meanwhile, since the optical force acting on the probe tip is predominantly along the z-direction, the total optical force can be expressed as:

$$F_z = \frac{1}{2} Re \left\{ \frac{\partial E_x^{loc}(r_t)^*}{\partial z} p_{t,x} + \frac{\partial E_y^{loc}(r_t)^*}{\partial z} p_{t,y} + \frac{\partial H_x^{loc}(r_t)^*}{\partial z} m_{t,x} + \frac{\partial H_y^{loc}(r_t)^*}{\partial z} m_{t,y} - \frac{ck^4}{6\pi} [p_{t,x}(m_{t,y})^* - p_{t,y}(m_{t,x})^*] \right\} \quad (17)$$

Under the quasi-static condition of $k_0 d \ll 1$, the variation in the incident field along the z-direction is relatively slow compared to the scattered near-field. Therefore, the phase term in the Green's function can be neglected, and the approximation $\partial G_0 / \partial z \approx -3/(4\pi d^4)$ can be adopted. Consequently, the approximate expressions for the components of the optical force can be obtained as:

$$F_z^e \approx \frac{3}{8\pi d^4 \varepsilon_0} Re(-p_{s,x}^* p_{t,x} - p_{s,y}^* p_{t,y}), \quad (18)$$

$$F_z^m \approx \frac{3}{8\pi d^4 \mu_0} Re(-m_{s,x}^* m_{t,x} - m_{s,y}^* m_{t,y}), \quad (19)$$

$$F_z^{em} \approx -\frac{ck^4}{12\pi} Re[p_{t,x}(m_{t,y})^* - p_{t,y}(m_{t,x})^*], \quad (20)$$

The electric and magnetic dipole moments of the tip and sample are solved self-consistently through the coupled local-field equations and dyadic Green functions. Therefore, the mutual tip-sample interaction is retained at the dipolar level. The analytical model assumes a homogeneous background and does not explicitly include the substrate. The changes in the optical force and differential force caused by finite-size effects, higher-order multipoles, retardation, and substrate-induced field redistribution are evaluated using full-wave simulations in the following section. The probe is represented by a spherical apex in the present model. This simplified geometry captures the local electric and magnetic response of the apex and facilitates the analysis of the tip-sample interaction. However, a practical PiFM probe also contains a conical shaft and cantilever, which may modify the local field, resonance condition, and force gradient. The present model should therefore be regarded as a qualitative or semi-quantitative apex model rather than as a calibrated description of a specific experimental probe.

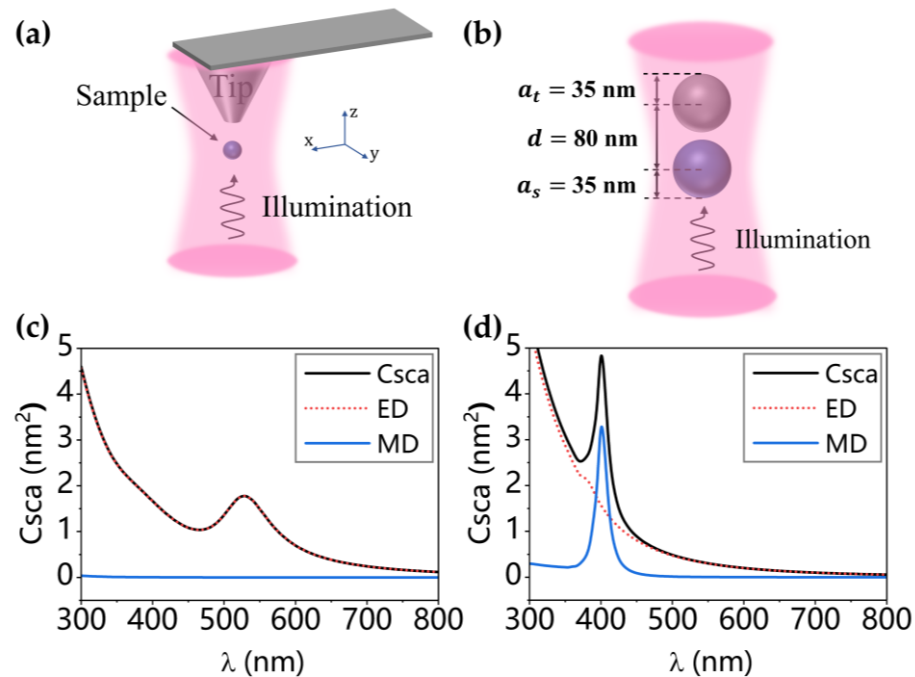


Figure 1. (a) Schematic diagram of the light-induced force microscope. (b) Simplified model of the coupled system consisting of the probe tip and the sample under test. (c) Scattering spectrum of a spherical Au nanoparticle. (d) Scattering spectrum of a spherical Si nanoparticle. The black sphere represents the simplified model of the tip, the blue sphere represents the simplified model of the sample, and the pink region schematically illustrates the incident optical field.

3. Results and Discussion

In previous studies, the detection of light-induced forces mainly relied on metallic probes. Such probes typically exhibit a significant electric dipole response, while their magnetic response is relatively weak, thereby limiting the role of local magnetic field effects and related optomagnetic effects in light-induced force detection. Therefore, this work attempts to employ semiconductor probes for light-induced force detection. This is mainly because high-index semiconductor nanoparticles can support not only a strong electric response, but also a much stronger magnetic response, thus offering a new way to enhance chirality-dependent optical force signals. In the following calculations, the radii of both the sample and the probe tip are assumed to be 35 nm, and the incident field is a plane wave propagating along the z-direction. As shown in Figure 1c,d, where C_{sca} represents the scattering cross-section, ED and MD denote the electric dipole and magnetic dipole contributions to the scattering cross-section, respectively. We calculated the scattering spectra of gold and silicon nanoparticles, respectively. The results show that the electric dipole resonance peak of the gold particle is located at 530 nm, while its magnetic dipole scattering contribution is very weak and thus negligible. In contrast, the silicon particle exhibits a distinct magnetic dipole resonance peak at 407 nm, and its total scattering cross-section is larger. Based on above results, this work selects 530 nm and 407 nm as the representative operating wavelengths for the gold probe and silicon probe, respectively, to compare the optical force responses of the two probe materials under their respective dominant resonance conditions.

In studies of chiral characterization based on photo-induced force microscopy, circularly polarized light is commonly used as the excitation source. Superchiral fields possess a higher optical chirality density than circularly polarized light and have been shown to play an important role in enhancing circular dichroism signals of chiral molecules; however, their influence on optical force effects has not yet been systematically investigated.

To this end, a superchiral optical needle field is employed in this work as the excitation field for the probe–sample coupled system. This optical needle field can be generated by tightly focusing a first-order radially polarized Bessel–Gaussian beam onto the end face of a photonic crystal [45]. Figure 2 shows the spatial distribution of the superchiral optical needle field. A superchiral hotspot with an enhancement of about 15 times is clearly observed in the central region, and the field maintains good lateral confinement during propagation. Since the chirality of the superchiral optical field is determined by the topological charge m of the radially polarized vortex, $m = \pm 1$ correspond to a pair of superchiral optical fields with opposite chiralities. In this work, the optical force difference generated by these fields acting on the probe tip is defined as $\Delta F = F_{m=1} - F_{m=-1}$.

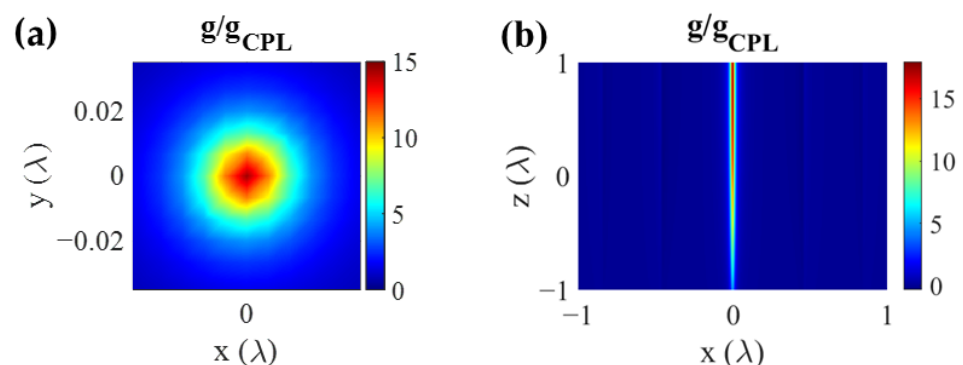


Figure 2. Distribution of the superchirality factor of the superchiral optical field in the (a) xy plane and (b) xz plane.

The expressions for the electric and magnetic fields of the superchiral optical needle are as follows [45]:

$$\begin{aligned} E_r(r, \phi, z) = & A \int_{a\theta_c}^{\theta_{NA}} P(\theta) \sin \theta \sqrt{1 - \left(\frac{n_i}{n_t}\right)^2 \sin^2 \theta} \exp(in_t k_0 z \sqrt{1 - \left(\frac{n_i}{n_t}\right)^2 \sin^2 \theta}) \\ & \times \exp(im\phi) t^{(p)} [J_{m+1}(n_i k_0 \rho \sin \theta) - J_{m-1}(n_i k_0 \rho \sin \theta)] d\theta, \end{aligned} \quad (21)$$

$$\begin{aligned} E_\phi(r, \phi, z) = & -iA \int_{a\theta_c}^{\theta_{NA}} P(\theta) \sin \theta \sqrt{1 - \left(\frac{n_i}{n_t}\right)^2 \sin^2 \theta} \exp(in_t k_0 z \sqrt{1 - \left(\frac{n_i}{n_t}\right)^2 \sin^2 \theta}) \\ & \times \exp(im\phi) t^{(p)} [J_{m+1}(n_i k_0 \rho \sin \theta) + J_{m-1}(n_i k_0 \rho \sin \theta)] d\theta, \end{aligned} \quad (22)$$

$$\begin{aligned} E_z(r, \phi, z) = & i2A \frac{n_i}{n_t} \int_{a\theta_c}^{\theta_{NA}} P(\theta) \sin^2 \theta \exp(in_t k_0 z \sqrt{1 - \left(\frac{n_i}{n_t}\right)^2 \sin^2 \theta}) \\ & \times \exp(im\phi) t^{(p)} J_m(n_i k_0 \rho \sin \theta) d\theta, \end{aligned} \quad (23)$$

$$\begin{aligned} H_r(r, \phi, z) = & -\frac{A}{Z_t} \int_{a\theta_c}^{\theta_{NA}} P(\theta) \sin \theta \exp(in_t k_0 z \sqrt{1 - \left(\frac{n_i}{n_t}\right)^2 \sin^2 \theta}) \\ & \times \exp(im\phi) t^{(p)} [J_{m+1}(n_i k_0 \rho \sin \theta) - J_{m-1}(n_i k_0 \rho \sin \theta)] d\theta, \end{aligned} \quad (24)$$

$$H_\phi(r, \phi, z) = -\frac{iA}{Z_t} \int_{a\theta_c}^{\theta_{NA}} P(\theta) \sin \theta \exp(in_t k_0 z \sqrt{1 - \left(\frac{n_i}{n_t}\right)^2 \sin^2 \theta}) \quad (25)$$

$$\times \exp(im\varphi)t^{(p)}[J_{m+1}(n_i k_0 \rho \sin \theta) + J_{m-1}(n_i k_0 \rho \sin \theta)]d\theta,$$

$$H_z(r, \phi, z) = 0, \quad (26)$$

Here, $k_0 = 2\pi/\lambda$ is the wave vector in free space, $t^{(p)}$ is the transmission coefficient for p-polarized plane waves. $J_m(x)$ denotes the Bessel function of the first kind of order m , and $P(\theta)$ is the apodization function of the lens. $\theta_{\text{NA}} = \arcsin(\text{NA}/n_i)$ is the maximum focusing angle of the lens, where n_i is the refractive index of the lens. A is a constant related to the focal length and wavelength, whose magnitude is associated with the power. Z_t is the impedance of the ambient medium with refractive index n_t , θ_c denotes the incident angle, and a represents a variable factor adjusted by the incident angle. Based on the field expressions above, the normalized field distributions in the focal plane can be plotted, as shown in Figure 3. Equations (21)–(26) describe the prescribed incident superchiral field before the tip and sample are introduced. In the optical-force calculation, the local field additionally contains the particle-scattered contribution represented by the Green-function terms. Therefore, the field perturbation induced by the tip–sample interaction is included at the dipolar level. Nevertheless, finite-size effects, retardation, higher-order multipoles, and substrate-induced field redistribution are not fully represented in the analytical model and should be evaluated separately using full-wave simulations. However, a rigorous three-dimensional full-wave implementation of the prescribed angular-spectrum superchiral source has not yet been achieved in the present study. Therefore, the superchiral-field results should be interpreted as semi-quantitative theoretical predictions based on the coupled-dipole model, rather than as fully validated absolute-force calculations.

In the analytical point-dipole model, the incident superchiral field is evaluated at the particle centers. For the axially aligned tip–sample configuration, both centers lie on the optical axis. At these positions, the incident longitudinal electric-field component satisfies $E_z = 0$ by symmetry, while the incident longitudinal magnetic-field component H_z is identically zero. Equations (13)–(16) can therefore be used without additional incident longitudinal components within the point-dipole evaluation. This statement does not apply to the entire finite particle volume. A particle with a radius of 35 nm extends into off-axis regions where E_z is no longer negligible, and $|E_z|$ near the particle boundary can reach approximately 60% of its plotted peak value. The present point-dipole model does not resolve this spatial variation across the particle volume. The possible finite-volume contribution of the longitudinal electric field is therefore identified as a limitation of the present semi-quantitative model.

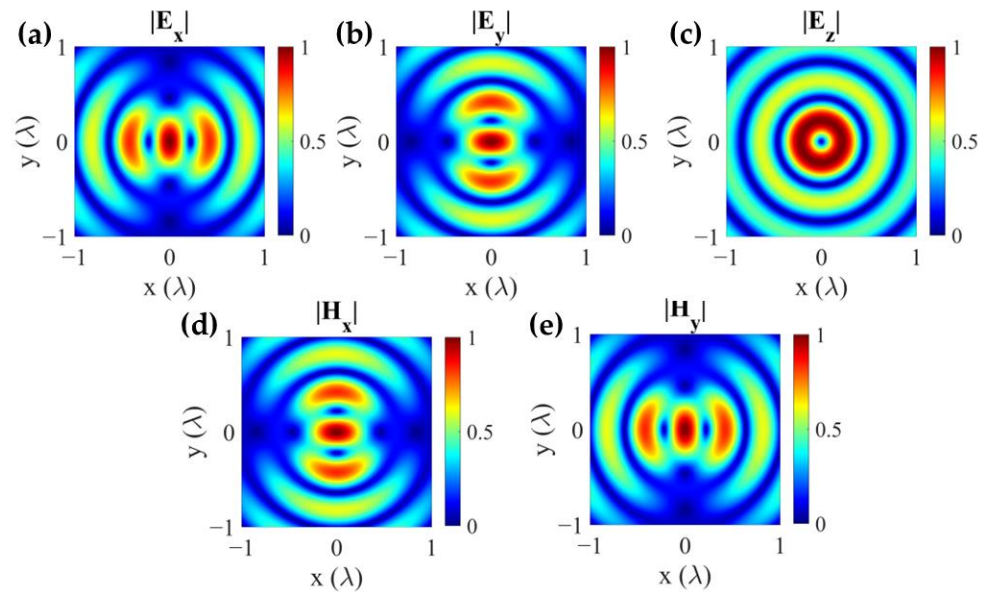


Figure 3. Distribution of the electric fields (a–c) and magnetic fields (d,e) of the superchiral optical field in the focal plane.

We first consider the enhancement effect of semiconductor probes on optical force detection. The z -components of the optical force acting on the probe tip under excitation by right-handed and left-handed circularly polarized plane waves, denoted as F_z^{RCP} and F_z^{LCP} , are calculated respectively, and their relationship with the chiral parameter κ is analyzed. The optical force difference is defined as $\Delta F = F_z^{\text{LCP}} - F_z^{\text{RCP}}$. Experimentally, the differential optical force can be obtained by periodically switching the handedness of the excitation field and synchronously detecting the resulting cantilever response. Specifically, the differential axial force is defined as $\Delta F_z = F_z^{(+)} - F_z^{(-)}$, where $F_z^{(+)}$ and $F_z^{(-)}$ denote the axial forces under two excitation states with opposite handedness. The handedness can be modulated using a photoelastic modulator, electro-optic modulator, liquid-crystal retarder, or rotating quarter-wave plate, combined with lock-in detection. Under ideal handedness reversal, the helicity-independent background is suppressed by subtraction, whereas the chirality-dependent response is retained. In a practical PiFM measurement, this force difference is detected through the corresponding modulation of the cantilever amplitude, phase, or resonance frequency. In the calculations, the incident optical power is taken as 100 mW, the relative permittivity of the gold probe at 530 nm is $\varepsilon_t = -4.5461 + 2.4577i$, and that of the silicon probe at 407 nm is $\varepsilon_t = 28.900 + 3.4950i$. Unless otherwise specified, any changes in the parameters will be stated explicitly.

To evaluate the validity of the coupled-dipole model and the influence of the substrate, full-wave finite-element simulations were performed for the nominal configuration, consisting of a 35 nm-radius Si tip and a 35 nm-radius chiral sample separated by a 10 nm gap. The system was illuminated by left- and right-handed circularly polarized light at a wavelength of 407 nm and an incident power of 100 mW. As shown in Figure 4a,b, the coupled-dipole model, the substrate-free full-wave simulation, and the full-wave simulation including a glass substrate exhibit the same qualitative dependence on the chirality parameter κ , although their absolute force magnitudes differ. Figure 4c shows that the substrate-free full-wave result preserves the sign, odd symmetry with respect to κ , zero crossing at $\kappa = 0$, and nearly linear κ -dependence predicted by the analytical model. As summarized in Table 1, the coupled-dipole model overestimates the substrate-free full-wave differential force by approximately 17–18%, indicating that it provides a semi-quantitative description of the strongly coupled 10 nm-gap configuration. The discrepancy is

attributed mainly to finite-size, retardation, and higher-order multipolar effects beyond the dipole approximation. The substrate effect was further evaluated by explicitly including a glass substrate with a refractive index of $n = 1.5$ in the full-wave geometry. The substrate changes the magnitude of the differential force by approximately 52% relative to the substrate-free full-wave result, while the sign, odd symmetry, zero crossing, and near-linear dependence on κ remain unchanged. Therefore, the substrate-free model is suitable for identifying the symmetry, sign, and relative trend of the chirality-dependent response in a homogeneous-reference system, whereas the substrate should be included when quantitatively predicting the absolute force magnitude.

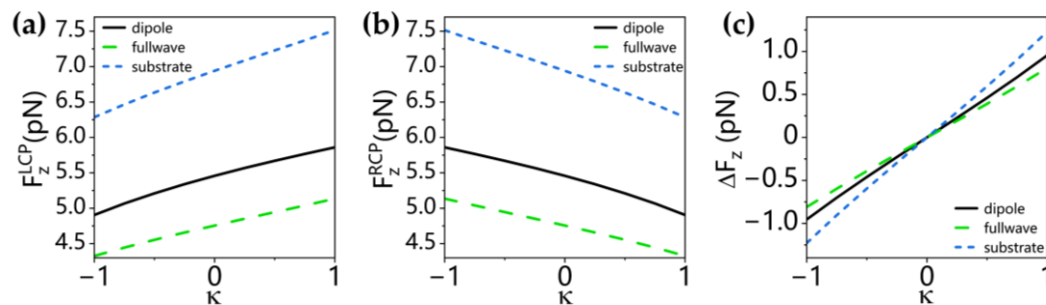


Figure 4. Comparison of the coupled-dipole and full-wave calculations for a Si probe at $\lambda_0 = 407$ nm and $P = 100$ mW. (a) Axial optical force under LCP illumination, (b) axial optical force under RCP illumination, and (c) differential axial force ΔF_z . The full-wave results are calculated both without a substrate and with a glass substrate of refractive index $n = 1.5$.

Table 1. Relative deviation of the coupled-dipole prediction from the substrate-free full-wave result and the relative change induced by the glass substrate.

κ	Dipole/Full-Wave Error	Substrate/Full-Wave Error
-1.00	17.9%	51.7%
-0.75	17.6%	51.7%
-0.50	17.3%	51.7%
-0.25	16.9%	51.4%
0.25	18.0%	52.7%
0.50	17.8%	52.4%
0.75	17.9%	52.2%
1.00	18.1%	52.0%

As shown in Figure 5a,c, the optical force difference generated by the silicon probe is significantly larger than that produced by the gold probe. According to the dipole approximation, the optical force difference on the gold probe mainly arises from the electric dipole term, whereas the contributions from the magnetic dipole term and the electromagnetic coupling term are both weak. In contrast, the magnetic dipole term in the silicon probe is significantly enhanced and acts in conjunction with the electric dipole term, resulting in a larger optical force difference for the same chiral parameter κ . When $\kappa = 1$, the optical force difference corresponding to the silicon probe is approximately twice that of the gold probe. This indicates that enhancing the magnetic response of the probe material helps amplify the optical force difference signal, thereby improving the characterization capability of light-induced force microscopy for the chiral parameter.

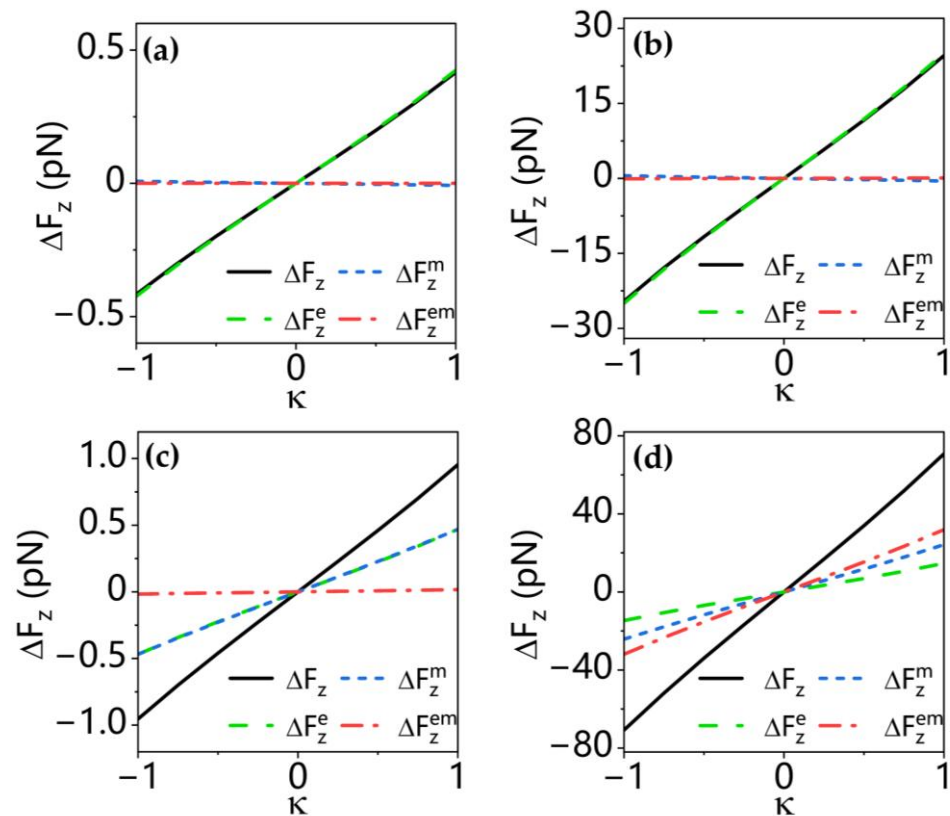


Figure 5. Comparison of the optical force difference acting on Au and Si tips as a function of the chirality parameter under different excitation fields. Panels (a,b) show the optical force difference acting on the Au tip under circularly polarized illumination and superchiral-field excitation, respectively, at the incident wavelength of 530 nm. Panels (c,d) show the corresponding results for the Si tip under circularly polarized illumination and superchiral-field excitation, respectively, at the incident wavelength of 407 nm.

In the present PiFM configuration, the cantilever response is primarily associated with the axial force F_z or its spatial gradient because the cantilever oscillation direction is taken to be the surface-normal z direction. This motivates the use of Equations (18)–(20) to describe the dominant measurable force response. The complete optical-force vector was also evaluated for the ideally aligned tip–sample configuration. As shown in Figure 6a, the transverse components F_x and F_y remain negligible compared with F_z because of the lateral symmetry of the system. The corresponding differential transverse forces, ΔF_x and ΔF_y , are zero within numerical precision, whereas ΔF_z carries the chirality-dependent response, as shown in Figure 6b. Therefore, the in-plane force components do not affect the extraction of κ under the ideal axial alignment considered here. Transverse forces may arise under misaligned, off-axis, or intentionally asymmetric conditions, which are beyond the scope of the present model.

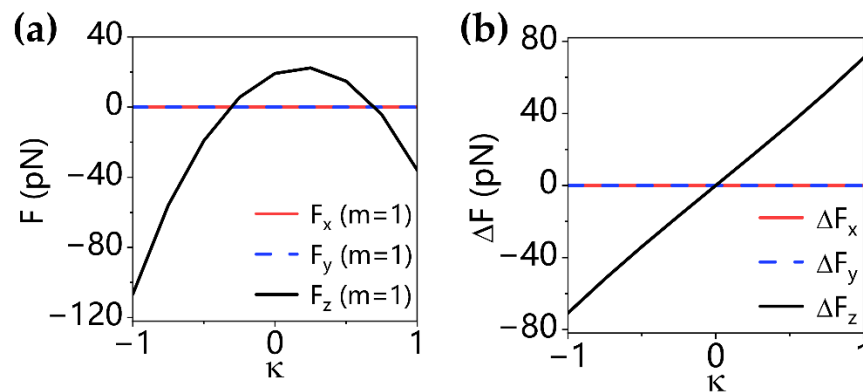


Figure 6. Optical-force components under superchiral excitation. (a) Components F_x , F_y , and F_z of the total optical force acting on the Si probe under one handedness of the superchiral field. (b) Differential force components ΔF_x , ΔF_y , and ΔF_z obtained from the two superchiral fields with opposite handedness.

Figure 5b,d show the dependence of the differential optical force on the chirality parameter κ for the gold and silicon probes, respectively, under excitation by the superchiral field at their corresponding resonance wavelengths. For a fair comparison, the time-averaged power transmitted through the focal plane is fixed at 100 mW for both the circularly polarized field and the superchiral field. For circularly polarized light, since its power distribution on the focal plane is approximately uniform, the total power can be obtained directly by integrating the energy flux density. For the superchiral optical field, its energy is mainly localized within a subwavelength range, with a full width at half maximum of approximately 0.26λ . Therefore, the optical power is first obtained by integrating the power flux density over the relevant cross-sectional area of the field. The amplitudes of the two excitation fields are then normalized so that the time-averaged power passing through the focal plane is 100 mW in both cases. Under this condition, for the same chiral parameter, the optical force difference induced by the superchiral optical field on the gold probe is approximately 50 times that under circularly polarized light excitation, while the enhancement on the silicon probe is even more significant, reaching approximately 60 times, as shown in Figure 5. Analysis of the decomposed terms of the differential optical force shows that this behavior arises because the superchiral field not only significantly enhances each dipolar contribution to the optical force, but also excites the magnetic response of the silicon probe more effectively, thereby markedly increasing the contributions of the magnetic dipole term and the electromagnetic coupling term to the optical force difference. Furthermore, compared to the benchmark scheme using circularly polarized light with a gold probe, the combination of a superchiral optical field and a silicon probe can enhance the optical force difference by approximately 140 times. Therefore, the superchiral optical field can effectively excite the equivalent magnetic dipole response of the tip, thereby significantly enhancing the chirality-related optical force signal.

The differential-force decomposition over the complete κ range shows that the enhancement is not produced by a single contribution. As shown in Figure 7, the electric contribution is substantial in both superchiral cases and is largest for the resonantly excited Au probe at 530 nm. In contrast, the magnetic-dipole and electric-magnetic coupling contributions become pronounced only for the Si probe under 407 nm superchiral excitation, while they remain small for the Au probe and under circularly polarized excitation. Therefore, the Si-superchiral enhancement results from the combined contributions of electric-field localization, magnetic-dipole response, and electric-magnetic coupling. The enhanced magnetic and coupling terms are the distinctive contributions enabled by the

resonant Si probe, whereas the approximately 140-fold enhancement should be interpreted as the combined effect of these contributions together with the electric term and local-field concentration.

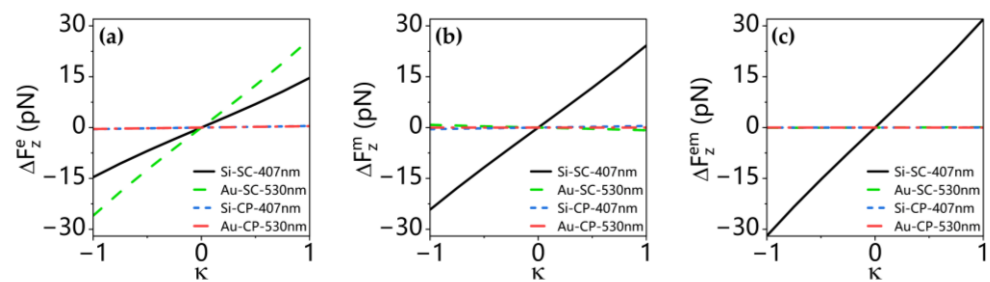


Figure 7. κ dependence of the electric (a), magnetic (b), and electric-magnetic coupling (c) contributions for Au-CPL, Si-CPL, Au-superchiral, and Si-superchiral cases.

To separate the material, wavelength, and resonance effects, controlled comparisons were performed at both common wavelengths. The Au and Si probes were compared at 407 nm and again at 530 nm under the same geometry, tip-sample gap, sample parameters, excitation type, and optical-power normalization. The resonance-optimized cases were analyzed separately. At $\kappa = 1$ under superchiral excitation, the differential force is approximately 26 pN for the Au probe at 407 nm and approximately 8 pN for the Si probe at 530 nm, as shown in Figure 8. Together with the resonance-optimized cases, these results demonstrate that there is no wavelength-independent ranking between the Au and Si probes. Instead, the enhancement is governed by the wavelength-dependent electric and magnetic response of the probe and its proximity to resonance. Therefore, the Au-Si difference should be interpreted as a resonance-assisted, wavelength-dependent probe-response enhancement rather than as a material effect alone.

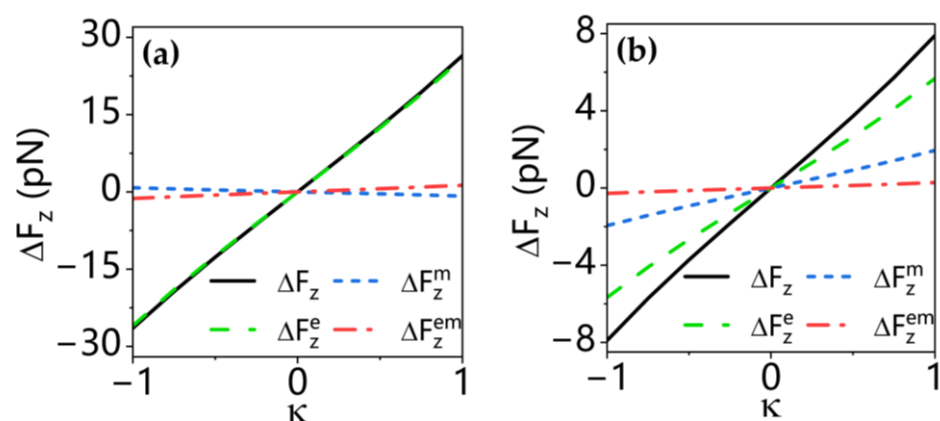


Figure 8. Comparison of superchiral-field excitation at non-resonant wavelengths under otherwise identical conditions. (a) Differential optical force generated by the Au probe under 407 nm superchiral-field excitation. (b) Differential optical force generated by the Si probe under 530 nm superchiral-field excitation.

Equal total transmitted power does not isolate optical chirality from local field concentration. The 100 mW comparison reflects the combined effects of subwavelength energy localization, enhanced optical chirality, field gradients, and probe response. Therefore, the approximately 140-fold enhancement should not be attributed to superchirality alone. To provide a more controlled comparison, the superchiral field was rescaled so that

its local electric-field amplitude at the particle position was equal to that of the 100 mW circularly polarized field, $|E_{SC}| = |E_{CP}| = 1.066448 \times 10^7 \text{ V m}^{-1}$. Under this normalization, the superchiral field carries 30.31 mW through the same integration aperture. The differential force remains approximately 20 times larger than that obtained under circularly polarized excitation using the same Si probe, as shown in Figure 9. This residual enhancement is associated with the different local optical chirality and spatial field structure after the dominant electric-amplitude difference has been removed. It is not a purely chirality-only factor because the magnetic field and field gradients are also different.

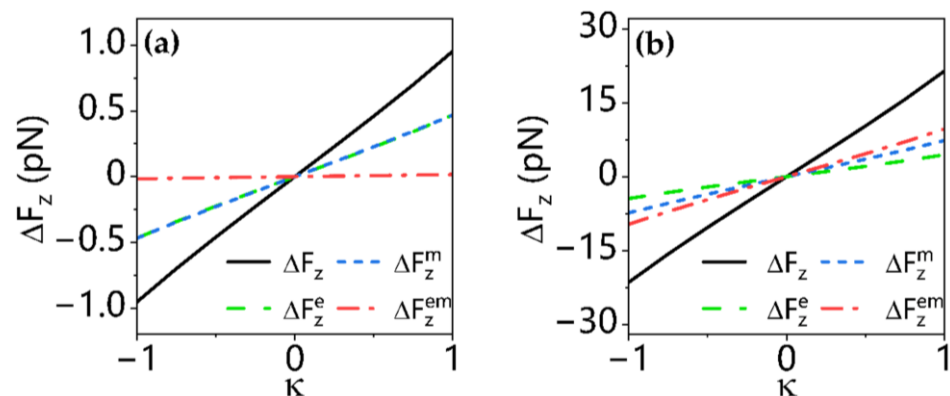


Figure 9. Differential-force decomposition on the Si tip under equal local electric-field amplitude for circularly polarized (a) and superchiral (b) excitation at the wavelength of 407 nm.

Based on the above analyses of the optical field distribution and probe enhancement characteristics, to further evaluate the detection capability of the superchiral optical field combined with a silicon probe for chiral nanoparticles, this work further investigates the variation in the optical force difference with respect to the chiral parameter and the radius of the sample, and compares it with the conventional scheme using circularly polarized light incidence with a gold probe. Considering the sensitivity of conventional optical force measurement systems, a differential optical force of 0.1 pN [39] is adopted here as the detection criterion, and the corresponding detection boundary is determined accordingly. The actual PiFM sensitivity depends on the cantilever stiffness k_c , quality factor Q , resonance frequency f_0 , modulation frequency, thermal noise, and measurement bandwidth. Therefore, 0.1 pN should not be regarded as a universal PiFM detection limit. It is used here only as a representative force-difference benchmark for comparing theoretical schemes and estimating projected detection thresholds. When the excitation handedness is modulated, the differential force ΔF_z acts as a harmonic driving force. Near a cantilever resonance, the displacement amplitude approximately scales as $A_{\text{mod}} \approx Q\Delta F_z/k_c$. In a force-gradient readout, the corresponding frequency shift is approximately $\Delta f \approx -[f_0/(2k_c)](\partial F_z/\partial z)$ [46]. Thus, the calculated optical force is related to the experimentally measurable cantilever response, although the exact sensitivity depends on the mechanical and detection parameters.

By jointly analyzing the minimum detectable threshold of the chirality parameter and the minimum detectable sample radius, the advantages of the superchiral-field-assisted silicon probe scheme for detecting weakly chiral and small-sized samples can be evaluated more directly. As shown in Figure 10a,b, when the sample radius is 35 nm, the minimum detectable chiral parameter threshold is 0.205 for the scheme using circularly polarized light incidence with a gold probe, whereas for the scheme using a superchiral optical field with a silicon probe, the minimum detectable threshold can be reduced to 0.0015. On the other hand, the minimum detectable sample radius for the superchiral optical field

with silicon probe scheme is also significantly reduced. When the chiral parameter $\kappa = 0.2$, the minimum detectable sample radii for the two schemes are 35 nm and 10 nm, respectively. The predicted values are model-dependent projections obtained under an idealized spherical geometry and an assumed 0.1 pN force-difference benchmark. They should therefore be regarded as projected theoretical thresholds rather than experimentally established detection limits. To evaluate the sensitivity of these estimates, the assumed force threshold was varied from 0.1 to 0.3 pN. The projected $\kappa_{\min}$ for a 35 nm-radius sample consequently increases from approximately 0.0015 to 0.0045, as shown in Figure 10c. For a sample with $\kappa = 0.2$, the projected minimum radius increases from approximately 10 to 15 nm, as shown in Figure 10d. The incident power and tip-sample gap were also independently varied by $\pm 10\%$, as summarized in Table 2. These results quantify the dependence of the projected detection thresholds on the principal model parameters.

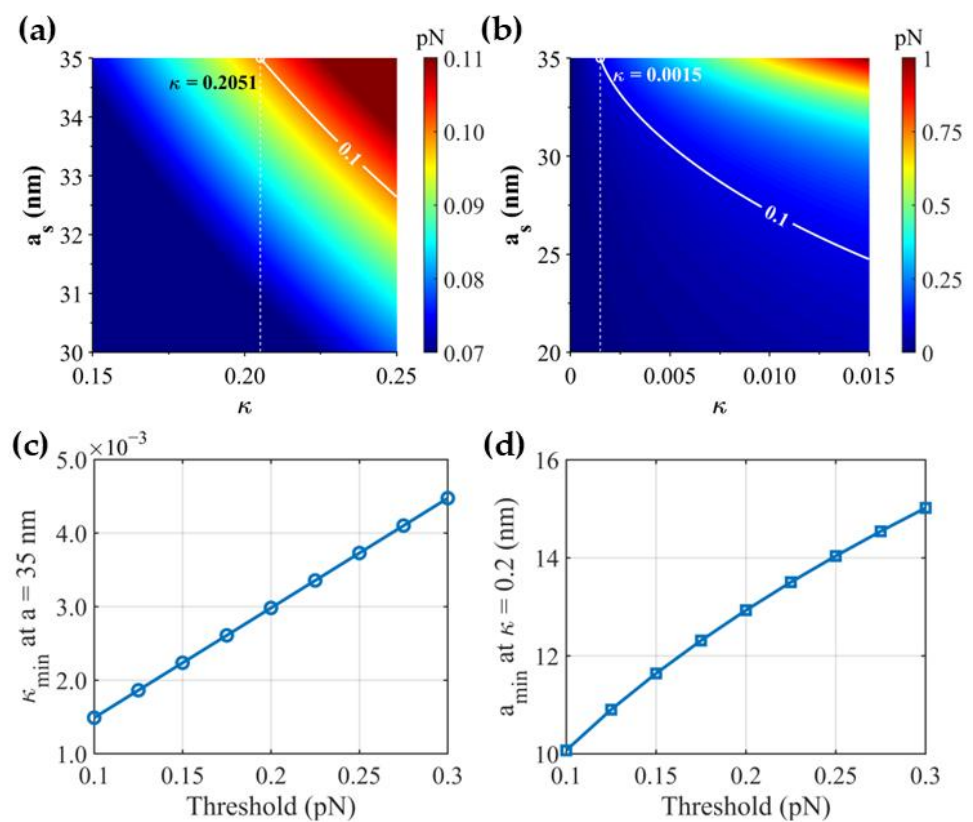


Figure 10. Distributions of the optical force difference ΔF as functions of the sample chirality parameter and radius. (a) Relationship between ΔF , the sample chirality parameter, and the sample radius for the Au tip under resonant excitation by circularly polarized light. (b) Relationship between ΔF , the sample chirality parameter, and the sample radius for the Si tip under resonant excitation by the superchiral optical field. Dependence of the projected chirality (c) and particle-size (d) thresholds on the assumed force sensitivity.

Table 2. Sensitivity of the projected performance to $\pm 10\%$ variations in power and tip-sample gap.

Case	Threshold (pN)	$\kappa_{\min}$ at $a = 35$ nm	$a_{\min}$ (nm) at $\kappa = 0.2$	ΔF_z (pN) at $a = 10$ nm, $\kappa = 0.2$
baseline	0.100	0.001492	10.074	0.09787
Power -10%	0.100	0.001657	10.457	0.08808
Power $+10\%$	0.100	0.001356	10.000	0.10765

Gap -10%	0.100	0.001423	10.000	0.11511
Gap +10%	0.100	0.001563	10.620	0.08369

Finally, the influence of tip position misalignment on the sensitivity of the detection technique is further investigated. Figure 11 shows the variation in the optical force difference as a function of the lateral displacement of the tip. We assume $a_s = a_t = 35$ nm, $d = 80$ nm, and a chiral sample with a chiral parameter $\kappa = 0.03$. As shown in Figure 11a, under the present model assumptions, the detectable region for a chiral sample with $\kappa = 0.03$ extends to an approximate radial distance of 73 nm from the tip. Figure 11b shows the influence of the lateral dislocation d_t between the tip-sample interaction system and the main optical axis on the detected optical force difference. Obviously, when $d_t = 0$, the optical force difference on the tip is maximized. For a chiral sample with a chiral parameter $\kappa = 0.03$, effective detection of the sample by the probe is predicted to be achieved within a lateral dislocation range of 85 nm. A comparison of these two cases shows that, as the spatial offset increases, the field intensity of the superchiral light field decreases accordingly, leading to a reduction in the differential optical force. These results indicate that the combined use of a semiconductor probe and a superchiral structured optical field can substantially enhance the capability of photo-induced force microscopy for detecting weakly chiral and small-sized samples. In addition, the measurement system exhibits strong robustness against spatial misalignment, providing a theoretical basis for the design of high-sensitivity photo-induced force chiral sensing schemes.

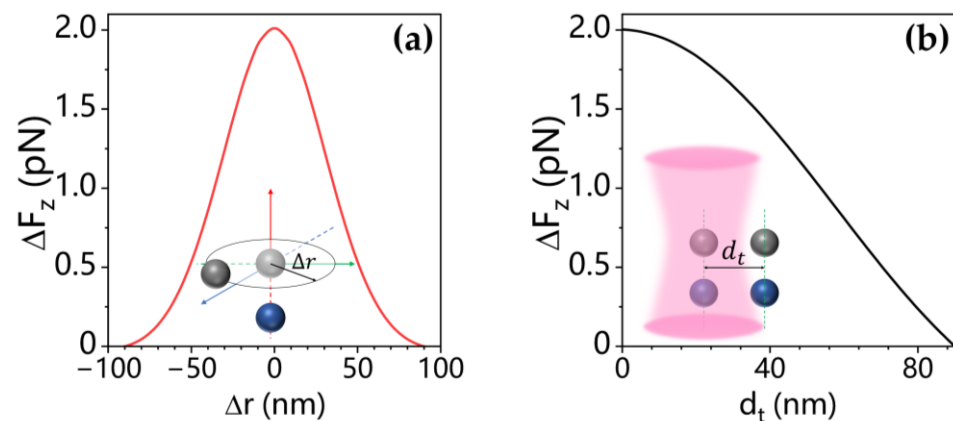


Figure 11. Variation in the optical force difference ΔF with the lateral displacement of the tip (a), and variation in the optical force difference ΔF with the lateral displacement of the tip-sample interaction system relative to the excitation beam (b) under the chiral parameter $\kappa = 0.03$. The black sphere represents the simplified model of the tip, the blue sphere represents the simplified model of the sample, and the pink region schematically illustrates the incident optical field. The green dashed line represents the central axis of the tip-sample model.

The present coupled-dipole model is applicable primarily to particles much smaller than the incident wavelength. For larger chiral particles, the differential-force principle may still be applied, but both the excitation field and electromagnetic model must be modified. The spatial extent of the superchiral region should be enlarged to provide sufficient overlap with the particle, which may be achieved by engineering the numerical aperture, pupil-field distribution, incident phase and amplitude, or topological charge. In addition, higher-order electric, magnetic, and magnetoelectric multipoles should be included using a multipole expansion, generalized Mie or T-matrix method, or a full-wave Maxwell-stress-tensor calculation. The present dipole model should therefore be regarded as the small-particle limit of the proposed approach.

4. Conclusions and Outlook

In summary, this work proposes a chiral PiFM enhancement strategy based on the coordinated use of a magnetic-dipole-responsive Si probe and a localized superchiral optical needle. The main contribution is not the isolated use of a semiconductor probe or a superchiral field alone, but their combined implementation to enhance the chirality-dependent differential force through the electric, magnetic, and electric–magnetic coupling contributions. The results show that, compared with circularly polarized illumination, the superchiral optical field can enhance the local optical chirality, field localization, and field-gradient distribution near the probe–sample gap. Under equal local electric-field amplitude and using the same Si probe, the superchiral excitation still produces an approximately 20-fold larger differential force than circularly polarized illumination. Relative to the Au-probe/CPL benchmark under equal total incident power, the combined Si-probe/superchiral-field scheme yields an approximately 140-fold enhancement of the differential optical force. Mechanism analysis indicates that this enhancement is not produced by a single contribution. Electric-field localization provides a substantial contribution, while the magnetic-dipole and electric–magnetic coupling terms become pronounced specifically for the resonant Si probe under 407 nm superchiral excitation. Thus, the enhanced response originates from the combined effects of local-field concentration, optical chirality, probe resonance, magnetic response, and electric–magnetic coupling. These results suggest that tailoring both the electromagnetic response of the probe and the local chirality distribution of the incident field provides a promising route for improving PiFM-based nanoscale chiral characterization. The present analysis offers a theoretical basis for detecting weakly chiral and small-volume samples, while the predicted enhancement and detection thresholds are based on a semi-quantitative theoretical model and remain to be verified using a realistic probe geometry and experimental PiFM measurements.

Author Contributions: Writing—original draft preparation, X.W.; writing—review and editing, G.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (12274074, 12134013) and the Natural Science Foundation of Jiangsu Province (BK20242024).

Data Availability Statement: The original contributions presented in this study are included in the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Tang, Y.; Cohen, A.E. Optical chirality and its interaction with matter. *Phys. Rev. Lett.* **2010**, *104*, 163901. <https://doi.org/10.1103/PhysRevLett.104.163901>.
2. Lekner, J. Optical properties of isotropic chiral media. *Pure Appl. Opt.* **1996**, *5*, 417–443. <https://doi.org/10.1088/0963-9659/5/4/008>.
3. Barron, L.D.; Buckingham, A.D. Rayleigh and Raman scattering from optically active molecules. *Mol. Phys.* **1971**, *20*, 1111–1119. <https://doi.org/10.1080/00268977100101091>.
4. Hug, W.; Surbeck, H. Vibrational Raman optical activity spectra recorded in perpendicular polarization. *Chem. Phys. Lett.* **1979**, *60*, 186–192. [https://doi.org/10.1016/0009-2614\(79\)80012-3](https://doi.org/10.1016/0009-2614(79)80012-3).
5. Barron, L.D. Raman optical activity. In *Optical Activity and Chiral Discrimination*; Mason, S.F., Ed.; Springer: New York, NY, USA, 1979; pp. 219–262. https://doi.org/10.1007/978-94-015-7644-4_9.
6. Barron, L.D.; Blanch, E.W.; Hecht, L. Unfolded proteins studied by Raman optical activity. *Adv. Protein Chem.* **2002**, *62*, 51–90. [https://doi.org/10.1016/S0065-3233\(02\)62005-4](https://doi.org/10.1016/S0065-3233(02)62005-4).
7. Johnson, W.C., Jr. Protein secondary structure and circular dichroism: A practical guide. *Proteins* **1990**, *7*, 205–214. <https://doi.org/10.1002/prot.340070302>.

8. Kelly, S.M.; Jess, T.J.; Price, N.C. How to study proteins by circular dichroism. *Biochim. Biophys. Acta* **2005**, *1751*, 119–139. <https://doi.org/10.1016/j.bbapap.2005.06.005>.
9. Greenfield, N.J. Using circular dichroism spectra to estimate protein secondary structure. *Nat. Protoc.* **2006**, *1*, 2876–2890. <https://doi.org/10.1038/nprot.2006.202>.
10. Hendry, E.; Carpy, T.; Johnston, J.; Popland, M.; Mikhaylovskiy, R.V.; Lapthorn, A.J.; Kelly, S.M.; Barron, L.D.; Gadegaard, N.; Kadodwala, M. Ultrasensitive detection and characterization of biomolecules using superchiral fields. *Nat. Nanotechnol.* **2010**, *5*, 783–787. <https://doi.org/10.1038/nnano.2010.209>.
11. Vázquez-Guardado, A.; Chanda, D. Superchiral light generation on degenerate achiral surfaces. *Phys. Rev. Lett.* **2018**, *120*, 137601. <https://doi.org/10.1103/PhysRevLett.120.137601>.
12. Tang, Y.; Cohen, A.E. Enhanced enantioselectivity in excitation of chiral molecules by superchiral light. *Science* **2011**, *332*, 333–336. <https://doi.org/10.1126/science.1202817>.
13. Van Kruining, K.C.; Cameron, R.P.; Götte, J.B. Superpositions of up to six plane waves without electric-field interference. *Optica* **2018**, *5*, 1091–1098. <https://doi.org/10.1364/OPTICA.5.001091>.
14. Grier, D.G. A revolution in optical manipulation. *Nature* **2003**, *424*, 810–816. <https://doi.org/10.1038/nature01935>.
15. Ashkin, A.; Dziedzic, J.M.; Bjorkholm, J.E.; Chu, S. Observation of a single-beam gradient force optical trap for dielectric particles. *Opt. Lett.* **1986**, *11*, 288–290. <https://doi.org/10.1364/OL.11.000288>.
16. Gao, D.; Ding, W.; Nieto-Vesperinas, M.; Ding, X.; Rahman, M.; Zhang, T.; Lim, C.; Qiu, C.-W. Optical manipulation from the microscale to the nanoscale: Fundamentals, advances and prospects. *Light Sci. Appl.* **2017**, *6*, e17039. <https://doi.org/10.1038/lsa.2017.39>.
17. Lin, L.; Wang, M.; Peng, X.; Liang, Z.; Li, S.; Luo, Z.; Cespedes, O.; Beckham, J.L.; Lei, Y.; Bao, Y.; et al. Opto-thermoelectric nanotweezers. *Nat. Photonics* **2018**, *12*, 195–201. <https://doi.org/10.1038/s41566-018-0134-3>.
18. Linghu, S.; Gu, Z.; Lu, J.; Yang, C.; Bao, Y.; Han, S.; Yang, H.; Yu, H.; Lin, L.; Wang, M. Plasmon-driven nanowire actuators for on-chip manipulation. *Nat. Commun.* **2021**, *12*, 385. <https://doi.org/10.1038/s41467-020-20683-2>.
19. Killian, J.L.; Ye, F.; Wang, M.D. Optical tweezers: A force to be reckoned with. *Cell* **2018**, *175*, 1445–1448. <https://doi.org/10.1016/j.cell.2018.11.019>.
20. Xin, H.; Li, Y.C.; Liu, Y.C.; Zhang, Y.; Lei, H.X.; Li, B.J. Optical forces: From fundamental to biological applications. *Adv. Mater.* **2020**, *32*, 2001994. <https://doi.org/10.1002/adma.202001994>.
21. Nan, F.; Rodríguez-Fortuño, F.J.; Yan, S.; Hsieh, P.; Zhang, M.; Ayala, K.; Gwo, S.; Lu, Y.-J. Creating tunable lateral optical forces through multipolar interplay in single nanowires. *Nat. Commun.* **2023**, *14*, 6361. <https://doi.org/10.1038/s41467-023-42076-x>.
22. Li, H.; Cao, Y.; Zhou, L.; Xu, X.; Zhu, T.; Shi, Y.; Qiu, C.-W.; Ding, W. Optical pulling forces and their applications. *Adv. Opt. Photonics* **2020**, *12*, 288–366. <https://doi.org/10.1364/AOP.378390>.
23. Chen, J.; Ng, J.; Lin, Z.; Chan, C.T. Optical pulling force. *Nat. Photonics* **2011**, *5*, 531–534. <https://doi.org/10.1038/nphoton.2011.153>.
24. Lu, J.; Yang, H.; Zhou, L.; Gao, D.; Lai, Y.; Ding, W.; Wang, M.; Qiu, C.-W. Light-induced pulling and pushing by the synergic effect of optical force and photophoretic force. *Phys. Rev. Lett.* **2017**, *118*, 043601. <https://doi.org/10.1103/PhysRevLett.118.043601>.
25. Ma, J.; Feng, L.; Sun, Z.; Zhang, H.; Xu, H.; Lin, J.; Zhou, L.; Wang, B.; Ding, W. Bipolar optical force on a dipolar nanoparticle: Thermally induced switching between optical pulling and optical pushing. *Phys. Rev. B* **2023**, *108*, 134308. <https://doi.org/10.1103/PhysRevB.108.134308>.
26. Yamanishi, J.; Ahn, H.Y.; Yamane, H.; Soukoulis, C.M.; Ozbay, E.; Käll, M. Optical gradient force on chiral particles. *Sci. Adv.* **2022**, *8*, eabq2604. <https://doi.org/10.1126/sciadv.abq2604>.
27. Tang, X.; Kuai, Y.; Fan, Z.; Wang, Y.; Zheng, L.; Wang, Z.; Li, Y.; Li, X.; Wang, J. Achiral and chiral optical force within topological optical lattices generated with plasmonic metasurfaces and tunable incident beam. *Phys. Rev. Appl.* **2023**, *19*, 054016. <https://doi.org/10.1103/PhysRevApplied.19.054016>.
28. Genet, C. Chiral light-chiral matter interactions: An optical force perspective. *ACS Photonics* **2022**, *9*, 319–332. <https://doi.org/10.1021/acsp Photonics.1c01130>.
29. Li, Y.; Rui, G.; Zhou, S.; Gu, B.; Yu, Y.; Cui, Y.; Zhan, Q. Enantioselective optical trapping of chiral nanoparticles using a transverse optical needle field with a transverse spin. *Opt. Express* **2020**, *28*, 27808–27822. <https://doi.org/10.1364/OE.403556>.
30. Tkachenko, G.; Brasselet, E. Optofluidic sorting of material chirality by chiral light. *Nat. Commun.* **2014**, *5*, 3577. <https://doi.org/10.1038/ncomms4577>.
31. Rukhlenko, I.D.; Teplakov, N.V.; Baimuratov, A.S.; Andronaki, S.A.; Gun'ko, Y.K.; Baranov, A.V.; Fedorov, A.V. Completely chiral optical force for enantioseparation. *Sci. Rep.* **2016**, *6*, 36884. <https://doi.org/10.1038/srep36884>.

32. Zhao, Y.; Saleh, A.A.E.; van de Haar, M.A.; Baum, B.; Briggs, J.A.; Lay, A.; Reyes-Becerra, O.A.; Dionne, J.A. Nanoscopic control and quantification of enantioselective optical forces. *Nat. Nanotechnol.* **2017**, *12*, 1055–1059. <https://doi.org/10.1038/nnano.2017.180>.
33. Rajapaksa, I.; Wickramasinghe, H.K. Raman spectroscopy and microscopy based on mechanical force detection. *Appl. Phys. Lett.* **2011**, *99*, 161103. <https://doi.org/10.1063/1.3652760>.
34. Nowak, D.; Morrison, W.; Wickramasinghe, H.K.; Jahng, J.; Potma, E.; Wan, L.; Ruiz, R.; Albrecht, T.R.; Schmidt, K.; Frommer, J.; et al. Nanoscale chemical imaging by photoinduced force microscopy. *Sci. Adv.* **2016**, *2*, e1501571. <https://doi.org/10.1126/sciadv.1501571>.
35. Jahng, J.; Brocious, J.; Fishman, D.A.; Yampolsky, S.; Nowak, D.; Tae Park, S.; Lee, K.-E.; Albrecht, T.R.; Potma, E.O. Gradient and scattering forces in photoinduced force microscopy. *Phys. Rev. B* **2014**, *90*, 155417. <https://doi.org/10.1103/PhysRevB.90.155417>.
36. Zeng, J.; Huang, F.; Guclu, C.; Veysi, M.; Noor, A.; Kamandi, M.; Jha, P.K.; Albooyeh, M.; Capolino, F.; Wickramasinghe, H.K. Sharply focused azimuthally polarized beams with magnetic dominance: Near-field characterization at nanoscale by photoinduced force microscopy. *ACS Photonics* **2018**, *5*, 390–397. <https://doi.org/10.1021/acsp Photonics.7b00816>.
37. Zeng, J.; Darvishzadeh-Varcheie, M.; Albooyeh, M.; Veysi, M.; Rajabali, S.; Noor, A.; Rajaei, M.; Kamandi, M.; Wickramasinghe, H.K. Exclusive magnetic excitation enabled by structured light illumination in a nanoscale Mie resonator. *ACS Nano* **2018**, *12*, 12159–12168. <https://doi.org/10.1021/acsnano.8b05778>.
38. Zeng, J.; Albooyeh, M.; Rajaei, M.; Noor, A.; Wickramasinghe, H.K. Direct detection of photoinduced magnetic force at the nanoscale reveals magnetic nearfield of structured light. *Sci. Adv.* **2022**, *8*, eadd0233. <https://doi.org/10.1126/sciadv.add0233>.
39. Kamandi, M.; Albooyeh, M.; Veysi, M.; Zeng, J.; Wickramasinghe, H.K. Unscrambling structured chirality with structured light at the nanoscale using photoinduced force. *ACS Photonics* **2018**, *5*, 4360–4370. <https://doi.org/10.1021/acsp Photonics.8b00765>.
40. Rui, G.; Ji, Y.; Gu, B.; Cui, Y.; Yu, Y.; Zhan, Q. Nanoscale chiral imaging under complex optical field excitation with controllable oriented chiral dipole moment. *Opt. Express* **2022**, *30*, 42696–42711. <https://doi.org/10.1364/OE.473133>.
41. Nieto-Vesperinas, M.; Sáenz, J.J.; Gómez-Medina, R.; Chantada, L. Optical forces on small magnetodielectric particles. *Opt. Express* **2010**, *18*, 11428–11443. <https://doi.org/10.1364/OE.18.011428>.
42. Varault, S.; Rolly, B.; Boudarham, G.; Demésy, G.; Stout, B.; Bonod, N. Multipolar effects on the dipolar polarizability of magneto-electric antennas. *Opt. Express* **2013**, *21*, 16444–16454. <https://doi.org/10.1364/OE.21.016444>.
43. Hanifeh, M.; Albooyeh, M.; Capolino, F. Optimally chiral light: Upper bound of helicity density of structured light for chirality detection of matter at nanoscale. *ACS Photonics* **2020**, *7*, 2682–2691. <https://doi.org/10.1021/acsp Photonics.0c00304>.
44. Bohren, C.F.; Huffman, D.R. *Absorption and Scattering of Light by Small Particles*; John Wiley & Sons: New York, NY, USA, 1998. <https://doi.org/10.1002/9783527618156>.
45. Rui, G.; Ying, X.; Zou, S.; Cui, Y.; Yu, Y.; Gu, B.; Zhan, Q. Enhanced circular dichroism of sparse nanoobjects by localized superchiral optical field. *J. Opt.* **2021**, *23*, 065002. <https://doi.org/10.1088/2040-8986/abf97b>.
46. Martin, Y.; Williams, C.C.; Wickramasinghe, H.K. Atomic force microscope-force mapping and profiling on a sub-100-A scale. *J. Appl. Phys.* **1987**, *61*, 4723–4729. <https://doi.org/10.1063/1.338807>.

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