

Near-field mechanical fingerprints for terahertz sensing of hidden nanoparticles in complex media

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Terahertz (THz) spectroscopy holds transformative potential for noninvasive sensing, yet characterizing individual nanoparticles in complex biological environments remains challenging due to the far-field diffraction limit. While near-field dipolar theory is well established, its application to characterizing/identifying nanoparticles immersed in complex media at THz frequencies is largely unexplored. This work utilizes numerical simulations of magneto-optical (MO) heterodimers—comprising n -doped indium antimonide ($[n\text{-InSb, GaSe}]$) and isotropic or birefringent particles (e.g., SiO_2 , GaSe)—under counterpropagating, circularly polarized THz illumination. The analytical framework is supported by a numerical validation against full-wave simulations. We demonstrate that while far-field observables like absorption cross sections are often dominated by the MO-active particle, mechanical variables—specifically induced binding forces and spin/orbital torques—exhibit superior sensitivity for detecting “hidden” neighboring components. Because these mechanical signatures depend directly on near-field interactions, they provide higher information density regarding interparticle coupling. Key findings reveal material-specific spectral “hot spots” and “zeros” that serve as robust calibration markers even within dispersive biological surrogates. We show that the spin torque on non-MO particles is significantly modified by MO-neighbor proximity, a phenomenon controllable via static magnetic fields. While experimental implementation in complex media presents significant challenges, our results establish a theoretical roadmap for using optomechanical signatures as high-resolution detection channels for diagnostics, signal transduction, and low-energy nanocircuit control.

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I. INTRODUCTION

The exploration of terahertz (THz) spectra has transitioned from a significant technological “gap” into one of the most promising frontiers for noninvasive sensing and theragnostic applications [1]. THz radiation possesses unique physical properties that facilitate deep penetration through

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nonpolar media—including polymers, ceramics, and dry biological tissues—which are often diffusive or opaque at visible or infrared wavelengths. Simultaneously, this regime is characterized by an exquisite sensitivity to the hydration states and rotational-vibrational transitions of polar environments, enabling real-time monitoring of molecular dynamics and phase changes at high resolution [2]. THz radiation’s nonionizing nature and sensitivity to tissue structure make it ideal for intraoperative mapping and cancer diagnosis [3]. Higher water content, combined with structural variations in tumoral tissues (increased cell and protein density), results in higher THz absorption and modified refractive indices. The “hyperthermia effect” offers another therapeutic path: Nanoparticles (NPs) can be irradiated with near-infrared or THz beams to induce surface plasmon excitation, raising the temperature of water in local cancer cells. This temperature change can then be imaged in real time with THz radiation [4]. Recent advancements have introduced novel photoactive materials, optimized device structures, and sophisticated detection mechanisms such as THz time-domain spectroscopy (THz-TDS) and scanning near-field optical microscopy (THz-SNOM) [5,6]. These developments have paved the way for advanced biomedical research, security screening, and 6G communications.

Central to these advancements is the interaction between THz radiation and nanoscale matter, where the wavelength-to-particle size ratio allows for the manipulation of NPs as local perturbations of an effective medium rather than mere scattering centers. THz radiation overlaps with the energy range of water relaxational motions and the intermolecular vibrations of biomacromolecules, making it a unique probe for the hydration shells that surround proteins, DNA, and phospholipids [7]. These hydration shells are not static; they exhibit molecular dynamics on timescales ranging from picoseconds to microseconds, influencing the functional behavior of biological systems [2]. At the nanoscale, the physical response of objects to THz radiation is predominantly characterized by the Rayleigh scattering regime [8]. With wavelengths spanning approximately in the 1–50 THz range, a nanoparticle system remains deep within this limit. In this framework, the particles do not independently diffuse the incident beam but function as local hot spots or perturbations that can maintain the coherence of the electromagnetic (EM) field. This coherence is fundamental for optomechanical manipulation, allowing for the precise application of optical forces and torques through interference and phase control [9].

In particular, a significant advancement in THz photonics involves the use of indium antimonide (InSb) and its most notable magneto-optical (MO) counterpart, *n*-doped InSb (briefly *n*-InSb) [10–13]. Unlike many materials that require high-intensity magnetic fields to exhibit MO effects, *n*-InSb demonstrates strong responses at modest fields due to its exceptionally low effective carrier mass [11,14]. This property enables the excitation of surface magnetoplasmons at room temperature, facilitating the creation of nonreciprocal devices that can steer or guide THz radiation at subwavelength scales [15].

In parallel with plasmonic materials, the use of III–VI semiconductors like gallium selenide (GaSe) provides a different modality for THz interaction. GaSe is a layered, negative uniaxial crystal [16,17] known for its high transparency and sharp phonon resonances in the THz regime. GaSe’s large birefringence and high figure of merit make it an ideal candidate for phase shifters, THz generation through optical rectification, and difference-frequency generation. The material’s mechanical response is orientation dependent, which, when integrated into a nanoparticle system, allows for the detection of individual particles based on their specific crystallographic alignment and phonon signatures.

The current landscape of THz sensing is dominated by two primary methodologies: far-field (FF) spectroscopy and near-field (NF) imaging [2]. While FF systems, such as THz-TDS, are effective for identifying collective molecular signatures and macroscopic hydration states, they are inherently limited by the diffraction limit. This constraint hinders the ability of FF systems to distinguish between individual NPs within a complex cluster, as the scattering and absorption cross sections often overlap and obscure local details. To overcome the diffraction limit, researchers have turned to THz-SNOM [6]. This technique utilizes a subwavelength aperture or a sharp metal nanotip to confine the EM field into a “hot spot” far smaller than the wavelength of the radiation

[8]. Recent reviews highlight the emergence of four distinct THz-SNOM modalities, offering spatial resolutions as fine as 20 nm [18].

The integration of metamaterials has further enhanced the sensitivity of THz biosensors [19]. By engineering metallic or dielectric microstructures, researchers can create split-ring resonators (SRRs) and chiral surfaces that exhibit unique EM resonance phenomena such as Fano resonances and toroidal modes [20]. These structures are highly sensitive to the local refractive index, enabling the detection of trace biochemical substances, viral pathogens, and glioma cell subtypes [19]. For instance, sensitivity can be improved by a factor of 13 by reducing the gap width in SRRs from 3 μm to 200 nm, facilitating the detection of viruses with diameters as small as 30 nm [21].

Despite the successes of NF imaging, a fundamental bottleneck remains in the ability to characterize and manipulate hidden NPs within complex, gelatinous environments typical of biological media. Recent theoretical work proposes that MO binding forces and torques can serve as high-resolution “local probes” that provide information inaccessible to FF observables [22,23]. Optical binding refers to the interparticle interaction induced by light between two or more objects [24,25]. In the Rayleigh regime, this interaction can be modeled using a coupled-dipole approach [26,27]. When two particles are illuminated by counterpropagating plane waves, they experience forces that depend on the phase and intensity gradients of the local field. The introduction of a static magnetic field to an MO-active dimer (e.g., *n*-InSb) breaks the symmetry of the system. This nonreciprocity results in tunable interparticle forces and spins that can be used to assemble or disassemble “optical matter” at will [28]. Crucially, while FF absorption may be dominated by a “large” MO particle, other NF mechanical magnitudes remain highly sensitive to the proximity and material properties of a second, maybe smaller particle. In addition to linear forces, the angular momentum of the THz field—both spin and orbital—can be transferred to the particles, exerting torques [29,30]. Spin torque arises from the interaction between the field’s polarization and the particle’s dipole moment, while orbital torque is related to the spatial distribution of the field [31]. In MO systems, these torques are coupled and can be modified by the external magnetic field, providing a unique mechanical signature that identifies the type of mode being excited [32]. In addition, MO nanocarriers could be loaded with therapeutic molecules and guided within the body using external magnetic fields, while their position is monitored through the mechanical fingerprints described above. Single NPs, such as gold NPs or InSb-based resonators, can be used to “turn off” or modulate THz resonances in slot antennas, providing a way to detect ultralow densities of biomolecules and lipid vesicles [33].

Following the methodology established in previous work—utilizing a dual counterpropagating plane wave setup to achieve a specific stationary field [23,32]—the response of MO heterodimers (i.e., dimers of dissimilar particles) is analyzed in both parallel and perpendicular configurations relative to an external magnetic field. This dimer arrangement serves as a fundamental geometric model to illustrate the underlying physical concepts of interparticle coupling. It is demonstrated that while traditional FF observables, such as absorption cross sections, often fail to distinguish individual particles within a dimer, NF mechanical variables offer superior sensitivity. Specifically, it is shown that induced binding forces and spin/orbital torques provide a robust method for identifying “hidden” particles and characterizing their resonances, even when they are obscured by the dominant absorption profile of the MO-active object or bigger particle. These results pave the way for advancing THz-based theragnostics, provide novel designs of THz antennas, and lead to the development of nanorobots/nanomachines working at low energy.

II. METHODOLOGY

To explore the behavior of NF mechanical variables, a theoretical framework is implemented based on the configuration illustrated in Fig. 1(a). This setup serves as a proof of concept, simulating a dual counterpropagating plane wave arrangement with identical left-handed circular polarization (LCP). Such a configuration is idealized to ensure that, in a reciprocal system, the net radiation pressure vanishes [23]; this allow interparticle forces to be isolated and studied with high

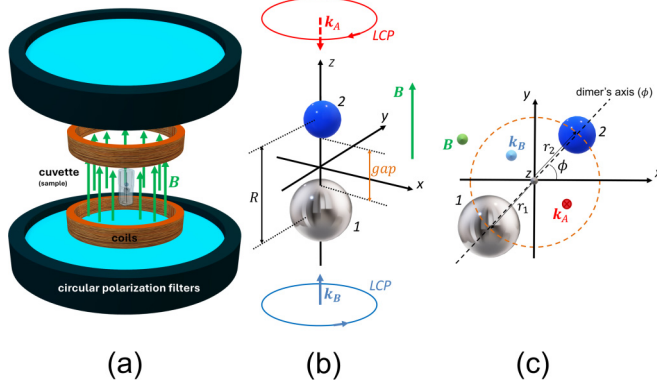


FIG. 1. (a) Schematic of a possible thought setup to study magneto-optical samples consisting of dimers with reduced mobility. The dimers are contained in a cuvette filled with, e.g., viscoelastic gel. The external (static) magnetic field ($\vec{B}$) is generated by Helmholtz coils, and the illumination field at THz is achieved by using appropriate polarization filters. Such beam is built with two counterpropagating plane waves, with wave vectors k_A and k_B , both waves possessing LCP. (b), (c) Details of the geometry and composition of the configurations studied in this work; the illuminating beam and $\vec{B}$ are always parallel to the z axis of the Cartesian coordinate system. (a) Parallel configuration, or dimer parallel to z . (b) Perpendicular configuration, where the dimer is held along the xy plane at $z = 0$. The first particle (silvered, No. 1) is made of n -doped InSb; the other particle (blue, No. 2) is made of an isotropic or birefringent material. The angle ϕ defines the position of the dimer's axis with respect to the coordinate system.

precision—a critical requirement for future experimental realization. The particles are modeled as being immersed in a cuvette filled with a viscoelastic gel, such as polyethylene or paraffin wax [34]. In the case of the wax, it is assumed in liquid state (between 46 and 68 °C) to avoid particle immobilization. In this simulated environment, the gel serves to damp thermal fluctuations and mimic the viscoelastic response of biological (soft) tissues or phantoms, effectively isolating the light-induced degrees of freedom [33]. The embedding media are assigned representative THz permittivity values, ranging from $\epsilon_{rb} = 1.75$ (PBS) to $\epsilon_{rb} \approx 4.0$ (hydrogels), to ensure that the results remain relevant to a broad class of biological surrogates [5]. Within this framework, the dimer's MO response is activated by a uniform magnetic field (B), conceptually generated by Helmholtz coils [Fig. 1(a)]. To provide a comprehensive analysis of the system's mechanical coupling, two fundamental geometric configurations are enforced: parallel [aligned with the z axis; Fig. 1(b)] and perpendicular [lying in the xy plane; Fig. 1(c)]. While these configurations are treated here as a computational model, i.e., the ones in Figs. 1(b) and 1(c), the sketch in Fig. 1(a) is designed to define the parameters and expected observables for subsequent THz-trap experimental validations.

As the particles considered are much smaller than the working wavelengths, they can be roughly modeled by their dipolar response. The particles 1 and 2 are then represented by dipole moments $\vec{p}_1$ and $\vec{p}_2$, respectively, defined as

$$\vec{p}_1 = \epsilon_0 \epsilon_{rb} \hat{\alpha}_1 \vec{E}_{\text{eff},1}, \quad (1)$$

$$\vec{p}_2 = \epsilon_0 \epsilon_{rb} \hat{\alpha}_2 \vec{E}_{\text{eff},2}, \quad (2)$$

where we use the definitions of the “effective” fields, $\vec{E}_{\text{eff},j}$, which are coupled by the Green tensor $\hat{G}$ [23] as

$$\vec{E}_{\text{eff},1} = \vec{E}_{0,1} + k_b^2 \hat{G} \hat{\alpha}_2 \vec{E}_{\text{eff},2}, \quad (3)$$

$$\vec{E}_{\text{eff},2} = \vec{E}_{0,2} + k_b^2 \hat{G} \hat{\alpha}_1 \vec{E}_{\text{eff},1}, \quad (4)$$

where $k_b = n_{rb}k_0$, such that n_{rb} is the refractive index and k_0 the vacuum wave number. We have also used the fact that the Green tensor is symmetric, i.e., $\hat{G}_{12} = \hat{G}_{21} \equiv \hat{G}$. The explicit definition of $\hat{G}$ can be found in Ref. [26]. Here, ϵ_0 is the vacuum permittivity, $\vec{E}_{0,n}$ is the incident electric field at the dipoles' positions $\vec{r}_n$, where $n = \{1, 2\}$, and $\hat{\alpha}_n$ is the polarizability tensor that represents the particles, which includes the radiative corrections when it is expressed as follows [35]:

$$\hat{\alpha} = \left(\hat{\alpha}_{n,0}^{-1} - \frac{ik_b^3 f}{6\pi} \right)^{-1}, \quad (5)$$

where $\hat{\alpha}_{n,0}$ are the quasistatic polarizabilities, which for spherical dipolar particles can be given by

$$\hat{\alpha}_{n,0}^{-1} = \frac{1}{V_n} (\hat{I}/3 + [\hat{\epsilon}_{r,n} - \hat{I}]^{-1}), \quad (6)$$

where V_n are the particle volumes and $\hat{\epsilon}_{r,n}$ their relative dielectric tensors. The explicit definition of the MO permittivity tensor function for n -InSb and the spectral behavior of their components can be found in Ref. [23]. It is not difficult to show that, by using Eqs. (3) and (4) into Eq. (1), the following solution is obtained:

$$\vec{p}_1 = \epsilon_0 \epsilon_{rb} \hat{F} (\vec{E}_{0,1} + k_b^2 \hat{G} \hat{\alpha}_2 \vec{E}_{0,2}), \quad (7)$$

where $\hat{F} = (\hat{\alpha}_1^{-1} - k_b^4 \hat{G} \hat{\alpha}_2 \hat{G})^{-1}$. Inserting this result into Eq. (4) by means of definition 1, we get

$$\vec{p}_2 = \epsilon_0 \epsilon_{rb} \hat{\alpha}_2 \left(\vec{E}_{0,2} + \frac{k_b^2}{\epsilon_0 \epsilon_{rb}} \hat{G} \vec{p}_1 \right). \quad (8)$$

The illumination consists of a superposition of two counterpropagating, LCP plane waves with the same intensity I_0 [30,36,37] (see Fig. 1), namely,

$$\vec{E}_0 = \frac{E_0}{\sqrt{2}} [(\check{y} - i\check{x})e^{ik_b z} + (\check{y} + i\check{x})e^{-ik_b z}]. \quad (9)$$

It is worth mentioning why this standing-wave field is chosen. This illumination easily creates a total field with zero-average values of $\nabla |\vec{E}|^2$, $\vec{S}$, and $\nabla \times \vec{J}_{\text{spin}}$, where $\vec{E}$, $\vec{S}$, and $\vec{J}_{\text{spin}}$ are the electric, Poynting, and spin density fields. In other words, this total field induces zero net force on an isotropic particle in the absence of a static magnetic field $\vec{B}$ [30]. Its total spin is always equal to zero, implying a null gradient force, while its helicity has a constant positive value, which implies a constant extinction force when $\vec{B}$ is on [23]. Besides avoiding complex optical traps, this illumination is homogeneous across space, which could help bind multiple particles to form large-scale optical matter, for example, using NPs and laser illumination.

The absorption cross section of the system can be calculated once the dipole moments are known by

$$\sigma_{\text{abs}} = \frac{k_b}{\epsilon_0^2 \epsilon_{rb}^2 |\vec{E}_0|^2} \text{Im} \{ \vec{p}_1 \cdot (\hat{\alpha}_{10}^{-1} \vec{p}_1)^* + \vec{p}_2 \cdot (\hat{\alpha}_{20}^{-1} \vec{p}_2)^* \}. \quad (10)$$

The i component of the forces exerted on each particle can be obtained from the time-averaged force within the Rayleigh approximation [38]. This is

$$F_{1,i} = \frac{1}{2} \text{Re} \{ \vec{p}_1^t [\partial_i \vec{E}^*(\vec{r}, \omega)]_{\vec{r}=\vec{r}_1} \}, \quad (11)$$

$$F_{2,i} = \frac{1}{2} \text{Re} \{ \vec{p}_2^t [\partial_i \vec{E}^*(\vec{r}, \omega)]_{\vec{r}=\vec{r}_2} \}, \quad (12)$$

where the derivatives of the total field $\partial_i \vec{E}(\vec{r}, \omega)|_{\vec{r}=\vec{r}_n}$ at the dipoles' positions $\vec{r}_n$ can be obtained from [39]

$$\partial_i \vec{E}(\vec{r}, \omega)|_{\vec{r}=\vec{r}_1} = \partial_i \vec{E}_0(\vec{r}, \omega)|_{\vec{r}=\vec{r}_1} + \frac{k_b^2}{\epsilon_0} (\partial_i \hat{G}(\vec{r}, \vec{r}_2))|_{\vec{r}=\vec{r}_1} \vec{p}_2, \quad (13)$$

$$\partial_i \vec{E}(\vec{r}, \omega)|_{\vec{r}=\vec{r}_2} = \partial_i \vec{E}_0(\vec{r}, \omega)|_{\vec{r}=\vec{r}_2} + \frac{k_b^2}{\epsilon_0} (\partial_i \hat{G}(\vec{r}_1, \vec{r}))|_{\vec{r}=\vec{r}_2} \vec{p}_1. \quad (14)$$

The total force exerted on the dimer results from adding the force components for each particle, namely, $F_{\text{tot},i} = F_{1,i} + F_{2,i}$. In particular, the net radiation pressure for the dimer under the illumination given by Eq. (9) is defined by taking $i = 3$, or the z components, as

$$F_{\text{tot},z} = F_{1,z} + F_{2,z}. \quad (15)$$

Another useful mechanical variable is the binding force, which in the present case is defined as

$$\Delta = (\vec{F}_1 - \vec{F}_2) \cdot \vec{n}, \quad (16)$$

where $\vec{n} = \frac{\vec{r}_2 - \vec{r}_1}{|\vec{r}_2 - \vec{r}_1|}$ is the dimer's versor. The optical torques can also be calculated, as given in Ref. [40]:

$$\vec{N}_{\text{spin},1} = \frac{1}{2\epsilon_0} \text{Re}\{\vec{p}_1 \times [(\hat{\alpha}_0^{-1})^* \vec{p}_1^*]\}, \quad (17)$$

$$\vec{N}_{\text{orb},1} = \vec{r}_1 \times \vec{F}_1, \quad (18)$$

$$\vec{N}_1 = \vec{N}_{\text{spin},1} + \vec{N}_{\text{orb},1}, \quad (19)$$

$$\vec{N}_{\text{spin},2} = \frac{1}{2\epsilon_0} \text{Re}\{\vec{p}_2 \times [(\hat{\alpha}_0^{-1})^* \vec{p}_2^*]\}, \quad (20)$$

$$\vec{N}_{\text{orb},2} = \vec{r}_2 \times \vec{F}_2, \quad (21)$$

$$\vec{N}_2 = \vec{N}_{\text{spin},2} + \vec{N}_{\text{orb},2}. \quad (22)$$

The definitions of the orbital and spin torques were discussed previously in Refs. [31,40], among others. The spin torques are always defined with respect to the centers of the particles. Otherwise, the reference system is located at the dimer's center of mass, and orbital torques are set.

III. RESULTS AND DISCUSSION

Specifically, all dimers calculated are composed of an n -InSb dipole as an MO-active particle (No. 1) of radius 50 nm and an another non-MO, smaller particle (particle 2, radius 25 nm). The interparticle gap in the dimers is kept relatively small, i.e., gap = 10 nm, since the interest lies in the NF sensing. Consequently, all the dimers are small compared to the wavelength $c/\text{frequency}$ of the illumination, their scattering cross sections being negligible, and the FF spectra are thus entirely characterized by the absorption cross sections. It is also necessary to point out that, under the illumination given by Eq. (9), the radiation pressures become negligible for all the systems studied in this work. No average z forces practically exist in the studied systems, i.e., $F_{\text{tot},z} \sim 0$ in Eq. (15).

A. Single particle

The baseline response of a single 100 nm n -InSb particle reveals the fundamental MO resonances that will appear below as well for dimers. As a matter of fact, two maps in Figs. 2(a) and 2(b) show the single-particle absorption and spin torques when the frequency and $B = |\vec{B}|$ are swept.

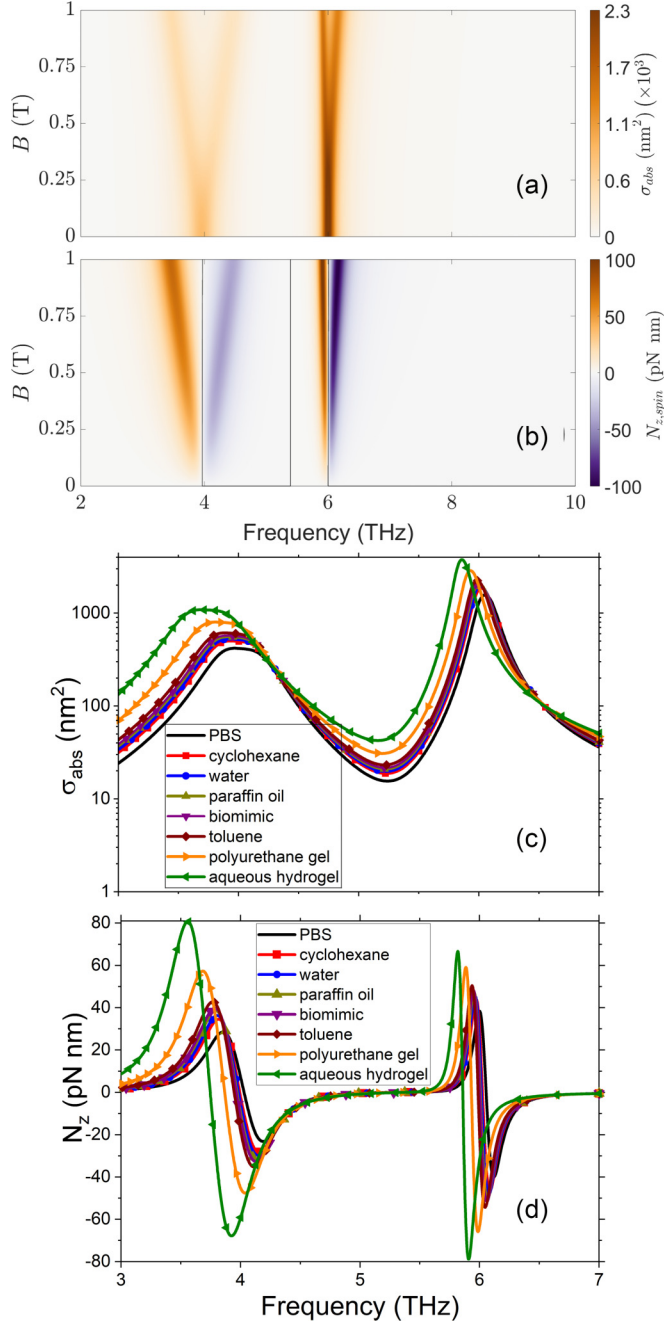


FIG. 2. Response by a single, 100 nm, MO particle (n -InSb) under the illumination described in Eq. (9). (a) Map of absorption cross section's spectra as a function of the external (static) magnetic field. (b) Same as panel (a), but for the spin torque exerted on the particle. The embedding medium is "biomimic." Black line highlights the zeros calculated for this observable. (c) Spectra showing the cross section's resonance peaks for several embedding media. Here, $B = 0.25$ T. (d) Same as panel (a), but for the resonant features in the spin torque.

Specifically, the absorption's map [Fig. 2(a)] shows a couple of resonances at $B = 0$ (B off, bottom values), which begin to split as the value of B increases (top). These correspond to phonon and plasmon polaritons typically found in n -InSb [41]. A critical observation is that the spin torque manifests these resonances in a way different than absorption does. The z spin changes sign according to branches produced by the particle's resonances, and the “zeros” in the spin torque spectrum align precisely with the resonance peaks when B is off. This establishes a robust method for detecting and calibrating the immersed system, as these zeros act as material-specific markers.

In addition, a variation of the embedding medium is included in the single-particle calculations [Figs. 2(c) and 2(d)]. Several realistic media are simulated, whose THz permittivity values correspond to the following: PBS, $\epsilon_{rb} = 1.75$; cyclohexane, 2.02; water, 2.1; paraffin oil, 2.2; a biological average mimic (labeled *biomimic* below), 2.25; toluene, 2.38; polyurethane gel, 3; and aqueous hydrogel, 4. The purpose of these results is to show that varying ϵ_{rb} between these values does not alter significantly the spectra of the single particle, with maybe the exception of high values such as those for polyurethane gel and aqueous hydrogel. Thus, the values to compare below the dimer's are quite similar except for some slight shifts in both frequency and intensity.

B. Dimer under parallel configuration

When a second particle is introduced in the parallel configuration [Fig. 1(b)], the coupling produces additional degrees of freedom. In a system where both particles are n -InSb, the absorption cross sections for the dimer and an isolated particle are nearly identical, because particle 1's absorption dominates; compare Figs. 3(a) and 3(b) for B on at 0.5 T and off, respectively. Noticeably, both the dimer and the isolated particle's responses (black line versus blue line) are very similar, in a way independent of the magnetic field used. Consequently, particle 2, which is smaller, is practically undetectable by the FF observable. Conversely, the NF-induced mechanics—specifically binding forces and spin torques—clearly distinguish the presence of the second particle [Figs. 3(c) and 3(d)]. The binding force in an [n -InSb, n -InSb] dimer is typically negative, indicating repulsive states in all the resonances shown in the absorption. Note the correspondence of the resonance features in both types of spectra. In particular, a sharp dip at 6 THz (phonon) corresponds to a strong repulsion exceeding 1 pN when $B = 0.5$ T, which reduces in magnitude if the magnetic field is further increased [Fig. 3(c)].

In general, the FFs can reflect the system's absorption or scattering. However, dynamic information as movement must in principle be connected to the NFs. NFs possess more information than FFs because of the interactions via evanescent waves. Figure 3 describes how more sensitive the NF mechanical variables can be compared to the typical FF variables. The spin torque induced on particle 2 is remarkably sensitive to the dimer's resonances [Fig. 3(d)].

The spin torque induced on particle 2 is remarkably strong [black line in Fig. 3(d)]. Noteworthy, $N_{z\epsilon}$ shows the characteristic resonances of the dimer, but in addition, the interparticle interaction drastically reduces their spectral values; compare the dimer response (black line) with the spin torque induced on particle 2 as it were isolated [blue line in Fig. 3(d)]. Moreover, the torque changes sign with sharp peaks each time a resonance is excited (black line), a behavior that differs significantly from an isolated particle of the same size, where the spin shows only positive peaks (blue line). This contrast underscores the role of interparticle interaction in modifying the local mechanical response. The spin seems to detect all the broken degenerations caused by the presence of $\vec{B}$.

Now the study describes a heterodimer [n -InSb, GaSe] immersed in biomimic, a system that has been designed to exhibit surface phonon resonances located near the surface phonon resonances for the n -InSb particle; this is another way to explore dielectric-particle detection properties. Gallium selenide (GaSe) is a hexagonal, birefringent crystal. Its permittivity tensor is diagonal when the coordinate system is aligned with its principal axes (x, y, z). In this orientation, the z

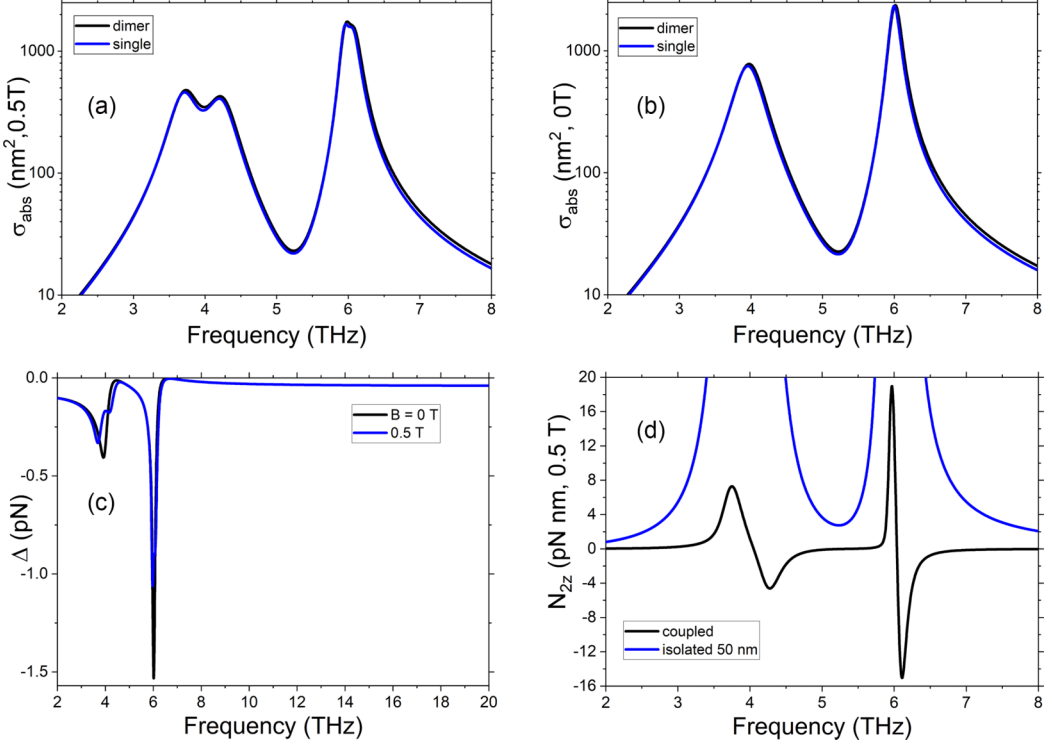


FIG. 3. Response by an MO heterodimer immersed in an average biological medium *biomimic* (sizes 100–50 nm, both particles made of *n*-InSb, immersed in biomimic, gap = 10 nm) under parallel configuration. (a), (b) Absorption cross sections when $B = 0.5$ T and $B = 0$ T, respectively. Black (blue) line for the dimer system (particle No.1 as isolated). (c) Binding force induced on the dimer when B is on/off. (d) Spin torque exerted on particle 2; black line when it is coupled to particle 1, blue when uncoupled (as isolated).

axis corresponds to the optic axis; thus, the tensor is expressed as [42]

$$\hat{\epsilon}_{r2} = \begin{bmatrix} \epsilon_{\perp} & 0 & 0 \\ 0 & \epsilon_{\perp} & 0 \\ 0 & 0 & \epsilon_{\parallel} \end{bmatrix}, \quad (23)$$

where $\epsilon_{\perp}$ is the ordinary component and $\epsilon_{\parallel}$ is the extraordinary component. GaSe is known for being a negative uniaxial crystal, meaning that $\epsilon_{\parallel} < \epsilon_{\perp}$. It is widely used for second harmonic and THz generation, being also a van der Waals material [16,17]. The $\epsilon_{\parallel}$ component (along the optical axis) is typically much lower than the in-plane $\epsilon_{\perp}$ because the electronic coupling between the layers (held by weak forces) is much weaker than the covalent bonding within a single layer. This material is modeled by a Lorentz oscillator (see details in the Appendix A for the effective parameters used).

For completeness, the spectra in Fig. 4 extend for a continuum of values of B ranging from 0 to 1 T. Note that the absorption displays the same scheme of resonances as that for the isolated *n*-InSb particle at frequencies around 4–6 THz, except for a single resonance at 7.2 THz, which results independent of B in the map, and is related to the phonons excited in GaSe particle [No. 2; Fig. 4(a)]. In other words, the spectra for low frequencies (<7 THz) are still dominated by the single-dipole response of the *n*-InSb particle. This fact can also be seen in the mechanical variables displayed in Figs. 4(b) and 4(c), namely, the binding force and the spin torque exerted on particle 2. Nevertheless, these observables display zero values (black lines), which means their

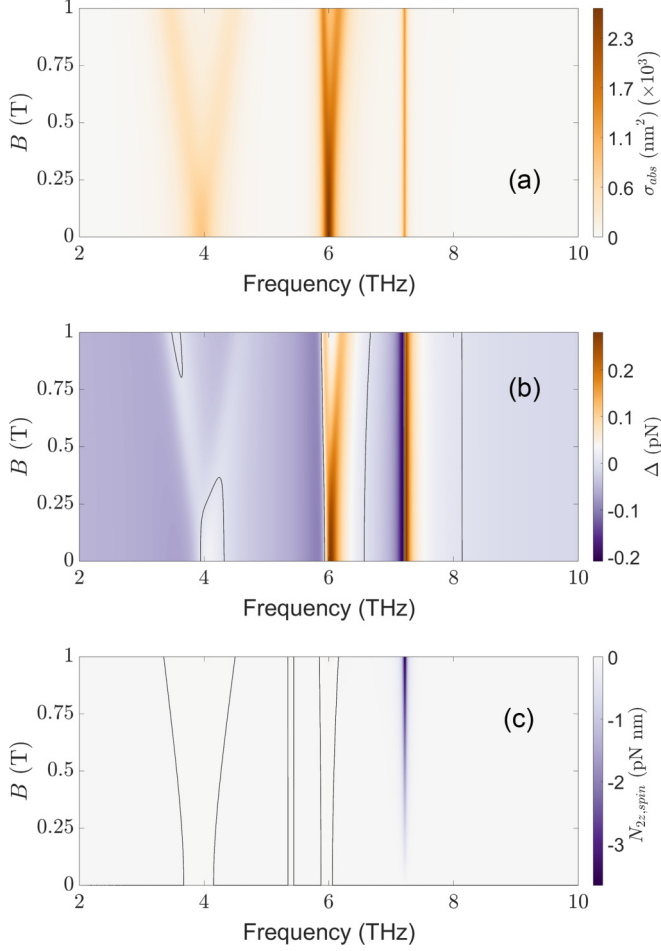


FIG. 4. Maps of relevant observables when both the frequency and value of the external magnetic field are swept. The heterodimer consists of a 100 nm particle (No. 1) made of n -InSb and a 50 nm particle (No. 2) of GaSe under parallel configuration, with a 10 nm gap. (a) Absorption cross section. (b) Binding force. (c) Spin torque exerted on the GaSe particle.

behavior at resonance is more complex than that for the absorption and thus more sensitive. For instance, the binding forces can help detect the second particle and characterize their associated resonances, because Δ describes the stability of the dimer (around $\Delta = 0$) in the momentum space. Specifically, for the GaSe particle, there is a sharp contrast between attraction ($\Delta > 0$) and repulsion ($\Delta < 0$) between the particles around the characteristic phonon resonance (~ 7 THz). Particle 2 is thus in “stable” (energetic) equilibrium when the illumination frequency is detuned from the phonon resonance. In other terms, more (less) energy in the system implies attractive (repulsive) forces. Crucially, the spin torque for the GaSe particle exhibits more atypical behavior [Fig. 4(c)]. In this case, the values for the torques are almost zero everywhere in the map except for the GaSe phonon resonance’s location. Furthermore, the intensity of the spin torque is strongly modified when B increases. This phenomenon can only be explained due to strong interparticle interaction, since particle 2 does not exhibit direct MO properties. Therefore, the spin torque as an observable displays more sensitivity to detect particle 2 than the other variables in the illustrated example.

Noteworthy, the gap between particles may vary on a larger scale to catch the effect of the stationary character of the incident beam. However, these gaps should be as large as a few millimeters for such effect to be noticed. The absorption grows sharply to reach almost a plateau value that approximately corresponds to the addition of the independent absorptions (particles as isolated, not shown here). The same situation is found for the spin torques, whose growing trend is similar for large gaps. On the contrary, the binding decays rapidly to zero as gap increases. In all the variables, there are oscillations below the order of 0.01% in the limit of large gaps due to the stationary-wave effect.

C. Dimer under perpendicular configuration

Transitioning the dimer to a perpendicular configuration [see Fig. 1(c)] introduces azimuthal dependency. In light of this, the system shows new degrees of freedom that can be described by the radial coordinate r and the azimuthal angle ϕ [Fig. 1(c)] so that the interparticle gap is now radial in this frame. The illumination field polarizes the particles according to their angular position. Overall, the illumination of Eq. (9) imposes a direction for the electric field that is variable with z . Therefore, the beam polarizes the particles according to their z positions. To simplify the interpretation of results, let us assume $z_1 = z_2 = 0$, which imposes a uniform electric field (with a single direction) along the xy plane. With the purpose of exploring the sensing capabilities of the MO heterodimer under this setting, Fig. 5 shows the case of the dimer [n -InSb, SiO₂] under a constant field of $B = 0.25$ T. Now there are four relevant variables, namely, absorption [Fig. 5(a)], binding force [Fig. 5(b)], spin torque exerted on particle 2 [Fig. 5(c)], and the orbital torque exerted on the whole dimer [Fig. 5(d)]. In particular, the SiO₂ particle displays two resonances around 14 and 33 THz, which correspond to the excitation of phonon polaritons [43]. Further, these special resonances are modulated by the dimer angle ϕ , giving maxima at 90° and 270° [Fig. 5(a)]. This is consistent with the fact that the illumination's electric field at $z = 0$ is presently oriented along the y axis. Thus, the dielectric particle makes the dimer notoriously sensitive to the polarization of the illumination field. The binding force displays a similar pattern, with a 45° resonance modulation [Fig. 5(b)]. Note also that the main spots in Δ coincide with the absorption maxima, located with 90° modulation. Moreover, the binding-force resonances of SiO₂ are “stable” in the sense described above for parallel configuration: Each spot has a “bimodal” structure due to a striking contrast between negative and positive values near resonance.

At this point, Δ shows that also the MO resonances located below 10 THz are modulated by angle. Therefore, Δ is more sensitive as observable than the absorption in FF. The absorption does not show such dependency on ϕ at low frequencies. Another consequence of this enhanced sensitivity in NFs is the complex pattern of zeros in the force [white lines in Fig. 5(b)]; the curves at low frequencies are strongly dependent on B , showing complex shapes. Such effect can also be seen in Figs. 5(c) and 5(d) for the induced torques.

Outstandingly, the torques also expose 45° resonance modulation [Figs. 5(c) and 5(d)]. Also, orbital torques show the same kind of bimodal spots as the ones in Δ [Fig. 5(d)]; the colors (signs) of the spots around the resonances also reverse with 90° modulation. For the orbital torques, however, such spots have a 45° phase difference; the “stability” criterion for the orbital torque is different. Another significant remark between both kinds of torques is about their kind of spot: N_{2z} has “monomodal” spots instead of the bimodal of the orbital torque [Figs. 5(c) and 5(d)]. As a result, the torques and radial forces are synchronized and the dimer must obey to a spin-orbit coupling mediated by light. This coupling allows for a clear method of identifying/detecting particles in the dimer, as the well-resolved, particular spots in Fig. 5(c) reveal. Finally, the response by the dimer [n -InSb, GaSe] under perpendicular configuration is examined for a low field of $B = 0.25$ T (Fig. 6). In this case, the absorption displays practically the same values as the absorption under parallel configuration [Fig. 6(a)]; compare with Fig. 4(a). Nonetheless, the angular modulation of these resonances is visibly absent. Again, the FF observable lacks relevant information of the dimer, in this case its orientation. In contrast, the binding force exhibits strong modulation with ϕ that maximizes

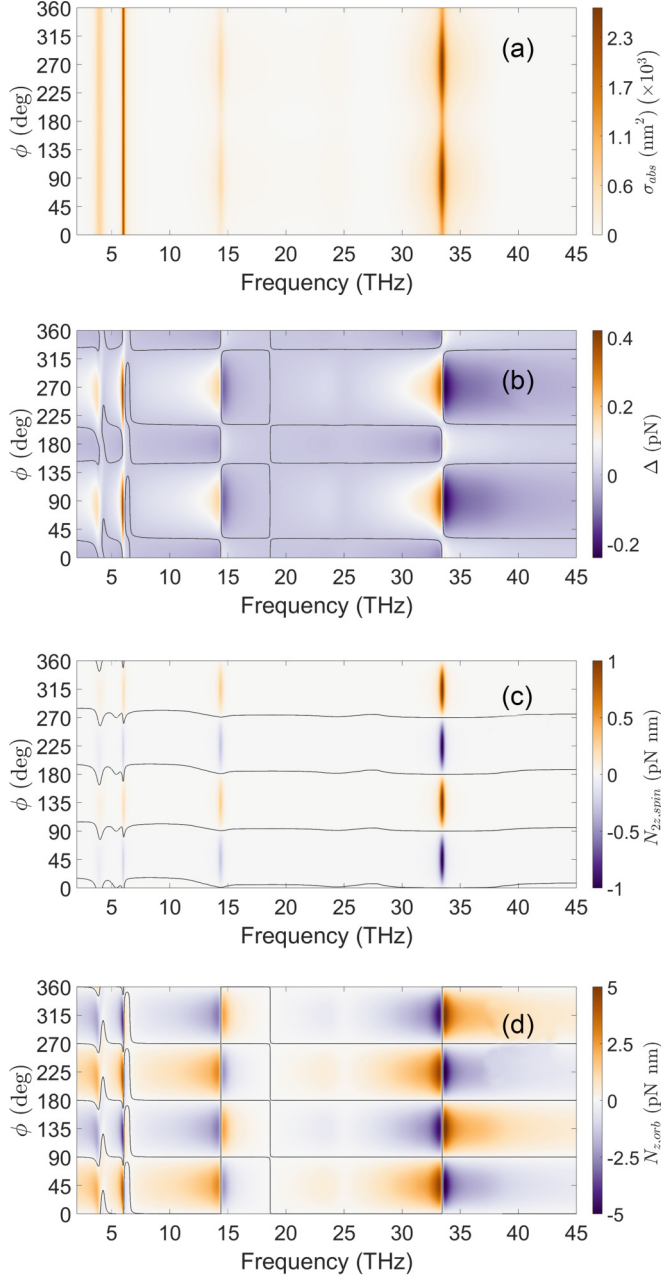


FIG. 5. Case of the dimer $[n\text{-InSb}, \text{SiO}_2]$ for perpendicular configuration and $B = 0.25\text{ T}$. The particles' sizes are 100 and 50 nm, respectively, with a 10 nm gap. (a) Absorption cross section. (b) Binding force. (c) z -Spin torque induced on the second particle. (d) z -Orbital torque induced on the system.

attraction at 90° and 270° for all the resonances. Their maxima are an order of magnitude higher than those in Fig. 4(b). In particular, the strongest spots show the bimodal structure (stability) like those shown in Fig. 5(b) for silica's case. The phonon resonance at 7.2 THz, corresponding to GaSe, appears as strong as the main MO resonance for $n\text{-InSb}$ at 6 THz. The map of Fig. 6(b) becomes naturally more complex than its analog for Fig. 4(b), showing an intricate resonance pattern of zeros

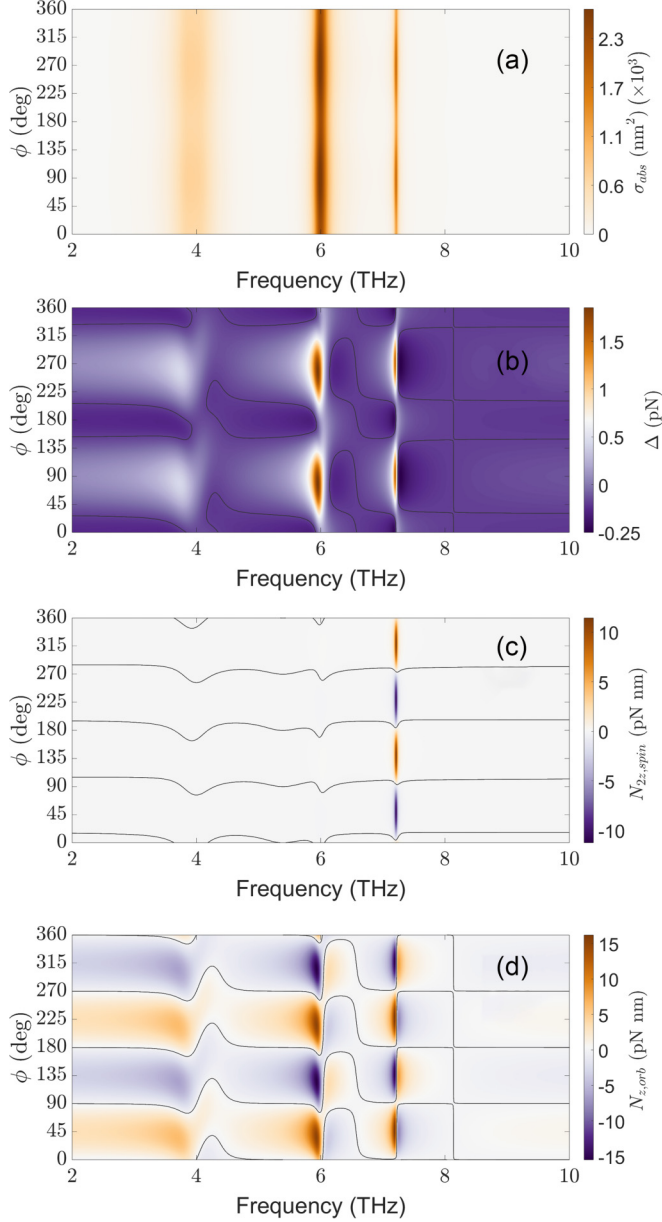


FIG. 6. Case of the dimer $[n\text{-InSb, GaSe}]$ for perpendicular configuration and $B = 0.25$ T. (a) Absorption cross section. (b) Binding force. (c) Spin torque induced on the second particle. (d) Orbital torque induced on the system.

(black lines). Analogous patterns of zeros appear also for the induced torques [Figs. 6(c) and 6(d)]. In addition, there are stronger and sharper spots than the previous cases analyzed. As an illustration, compare the values obtained for the absorption, binding, and torques calculated for SiO_2 's case [Figs. 5(a)–5(d)]; although in both systems, SiO_2 and GaSe, the absorption reaches maxima at a common value of 2300 nm^2 , the induced mechanical variables are very different. GaSe turns out to be much stronger and more detectable as a particle than SiO_2 , even though the geometries compared are equal.

The exhaustive study of MO dimers in the THz regime demonstrates that mechanical variables—binding forces, spin torques, and orbital torques—provide a superior and more nuanced understanding of light-matter interactions at the nanoscale [44]. Unlike conventional FF spectroscopy, which often masks the contribution of individual subunits within a cluster, NF mechanical probing acts as a high-resolution, dynamic diagnostic tool capable of identifying particles based on their specific resonant behaviors and crystallographic orientations.

Overall, the use of materials like *n*-InSb, which exhibits a significant MO response at low fields, and materials like GaSe, which provides sharp, anisotropic phonon signatures, allows for the creation of tunable, nonreciprocal systems. These systems can be effectively calibrated and monitored even when immersed in complex, viscoelastic biological mimics such as polyvinyl alcohol (PVA) hydrogels or paraffin wax. The sensitivity of these mechanical variables can be summarized by their ability to resolve the “hidden” components of a dimer:

1. Parallel binding forces: Act as proximity sensors, identifying particle 2’s presence and resonant stability.
2. Spin torques: Function as material identifiers, showing distinct sign changes and zeros that correlate with internal phonon and plasmon modes.
3. Orbital torques: Provide orientation sensitivity, revealing the azimuthal alignment of a dimer in a structured field. These are “readers” of the field’s polarization.

In essence, the proposed mechanical variables are in all cases studied more accurate and useful than the FF’s absorption as to serve for detection and sensitive reading of nearby particles. The examples shown support the fact that simple MO dimer systems could help detect (or work as) THz sources even in complex environments such as biological media. The presented results pave the way for assessing THz methods of *in vivo* theragnostics, THz communication, and design of nanomachines at low energies [45]. As a final thought, more complex systems than dimers could also be useful for detection and sensitivity in the embedding medium, such as multimers made of particles, pillars, or even waveguides and other MO couplers. These, however, would require further investigation provided they are expected to offer more degrees of freedom in terms of dynamics as well as more challenges to calibrate and control them. Other dimer configurations can also be studied, e.g., when radii and interparticle separations are swept; however, as the dimer is thought of as a probe for *in vivo* applications, the study is restricted to small particle sizes and interparticle separations. From the presented method, such an extension of the work can be easily implemented, possibly leading to more details about prototype design and ways of working.

D. Experimental feasibility and detection channels

While this work establishes the fundamental physical principles of near-field optomechanical coupling in soft media, several state-of-the-art experimental frameworks exist that could be adapted to detect these signatures. Piconewton-scale forces and femtonewton-meter or microradian torques are routinely resolved using polarization-resolved optical tweezers, where angular displacements and spin-momentum transfers are tracked with high fidelity via back-focal-plane interferometry [46,47]. In these configurations, changes in the spin or orbital angular momentum of the scattered light fields map directly to the mechanical torque experienced by the asymmetric nanoparticle dimer [48]. Furthermore, torque-amplitude spectroscopy can be deployed by modulating the intensity or polarization state of the incident THz fields, allowing researchers to isolate the specific optomechanical resonance frequencies of the hidden heterodimer from background thermal noise. In viscoelastic or microcrystalline soft matrices—such as the phantoms considered here—active magnetic torsional tweezers and rotational microrheology configurations demonstrate that micro- and nanoscale rotational displacements can be tracked dynamically to extract local mechanical responses [33,49].

In highly scattering or opaque environments like biological phantoms, direct optical tracking becomes limited. However, the high-contrast mechanical “fingerprints” predicted here could be

accessed via time-resolved photoacoustic and photothermal methods [50]. In such a setup, the modulated THz excitation of the heterodimer induces localized periodic thermal expansion, which is subsequently modulated by the surrounding medium's hydrodynamic drag and viscoelastic damping properties [33,51]. The resulting thermoelastic acoustic waves inherit a measurable phase delay and frequency modulation proportional to the near-field forces and local viscous constraints [33,52]. Detecting these acoustic signals provides an alternative, noninvasive channel to map near-field mechanical interactions deep within complex fluidlike and viscoelastic media [53].

IV. CONCLUSIONS

A new concept of near-field sensing has been theoretically demonstrated through the study of simple systems consisting of optically coupled nanoparticles. This framework allows for the construction of particle sensors and nanoscale calibration methods by utilizing the interaction between MO nanoparticles and nearby particles of any constitutive medium. Such systems are shown to be effective even when immersed in complex environments, such as biological phantoms, where far-field diffraction limits typically hinder characterization.

The proposed mechanical variables represent a radical advancement in the field of THz sensing by moving beyond the limitations inherent to the far field. By selecting dynamic observables with a direct relation to the local near fields, the environment of nanoparticle clusters can be explored with high precision. This approach leads toward the development of next-generation tools for nanomedicine and signal transduction. While the experimental detection of these piconewton-scale forces within biological phantoms remains a significant challenge, the results presented here establish a theoretical foundation for utilizing near-field mechanical signatures as a high-contrast alternative to traditional far-field THz spectroscopy. Transitioning these principles to point-of-care diagnostics will be critical for the future development of fiber-coupled nano-optomechanical sensors and portable THz metasurface platforms.

Beyond the calibration potential of isolated particles, the analysis of heterodimer systems highlights the emergence of unique mechanical fingerprints that are absent in far-field observables. Notably, for the [*n*-InSb, GaSe] dimer, the spin torque on the non-MO GaSe particle is driven entirely by strong near-field interaction with the neighboring MO particle. This coupling allows for the indirect magnetic control of the GaSe particle's mechanical state via the external static magnetic field, manifesting as a highly localized spectral signature at the GaSe phonon resonance. Furthermore, the sharp contrast between attractive and repulsive binding forces provides a "stability" criterion for characterizing these associated resonances and defining stable equilibrium points for particle trapping. These findings underscore the superior sensitivity of near-field mechanical variables for identifying "hidden" particles and resolving interparticle coupling.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain commercially sensitive information. The data are available from the authors upon reasonable request.

APPENDIX A: LORENTZ MODEL FOR GALLIUM SELENIDE

Following previous reports for this material, the dielectric function tensor components used in Eq. (23) were implemented using a Lorentzian oscillator model:

$$\epsilon_{\perp} = \epsilon_{\infty,\perp} + \frac{S_{\perp} \omega_{\text{TO},\perp}^2}{\omega_{\text{TO},\perp}^2 - \omega^2 - i\gamma_{\perp}\omega}, \quad (\text{A1})$$

$$\epsilon_{\parallel} = \epsilon_{\infty,\parallel} + \frac{S_{\parallel} \omega_{\text{TO},\parallel}^2}{\omega_{\text{TO},\parallel}^2 - \omega^2 - i\gamma_{\parallel}\omega}, \quad (\text{A2})$$

where the parameters for the ordinary ($\perp$) and extraordinary ($\parallel$) components are $\epsilon_{\infty,\perp} = 7.44$ and $\epsilon_{\infty,\parallel} = 5.76$ for the high-frequency dielectric constants, $\omega_{\text{TO},\perp} = 4.0310 \times 10^{13}$ rad/s and $\omega_{\text{TO},\parallel} = 4.4454 \times 10^{13}$ rad/s for the transverse optical phonon frequencies, $S_{\perp} = 3.16$ and $S_{\parallel} = 2.50$ for the oscillator strengths, and $\gamma_{\perp} = 3.7673 \times 10^{11}$ rad/s and $\gamma_{\parallel} = 5.6510 \times 10^{11}$ rad/s for the damping constants. These values align perfectly with well-established experimental data for single crystals in this material [54,55].

APPENDIX B: VALIDITY OF THE DIPOLE APPROXIMATION

To ensure that the dipolar response of the dimers provides an accurate representation of their full EM interaction, the analytical coupled dipole approximation (CDA)—which explicitly accounts for multiple scattering and radiative corrections—was benchmarked against full-wave numerical simulations performed via the finite element method (FEM). The CDA is also referred to as the discrete dipole approximation (DDA) since the number of dipoles equals the number of particles [56]. While the agreement between both methods was systematically verified across all configurations studied, a representative selection is presented here for the sake of conciseness.

In Figs. 7(a) and 8(a), the absorption efficiency is compared for the [*n*-InSb, GaSe] and [*n*-InSb, SiO₂] dimers, respectively. The excellent agreement observed in panel (a) of both figures confirms that for the particle sizes and interparticle distances considered, the dipolar contribution is the dominant mechanism. Consequently, the dimer as a whole behaves as an effective dipole moment for the FFs.

Furthermore, Figs. 7(b)–7(g) and 7(b)–8(g) display NF maps for the relative intensity of the electric field on a log₂ scale, superimposed with isolines. In these panels, the DDA and COMSOL simulations are directly compared. The FEM simulations reveal that the resonance profiles exhibit a pattern highly similar to the maps generated by the DDA (coupled dipoles). As characteristic of dipolar particles, their inner-field structures remain uniform, i.e., possessing constant values (left columns in Figs. 7 and 8), alongside a spatially decaying law and a lobular structure in the outer fields.

However, this inner-field uniformity is less pronounced in the FEM maps (right columns in Figs. 7 and 8), particularly at higher frequencies, providing clear evidence of multipolar field contributions. Nonetheless, these higher-order contributions play a significantly diminished role in the outer fields. The dipolar patterns remain dominant within the spectral regions of interest, and the theoretical framework rigorously captures the mechanical fingerprints of these heterodimers, which depend on the outer near fields via the Maxwell stress tensor formalism [26]. This dominance has been explicitly verified using the mechanical variables calculated by FEM, which are omitted here for the sake of brevity.

APPENDIX C: VARIATIONS OF THE SPIN TORQUE WITH THE SYSTEM'S GEOMETRY

To show the geometric dependence of the mechanical variables, which is illustrated with spin torque calculations, Fig. 9 indicates the response at 5.93 THz, a frequency where the torques reach their spectral maxima at $B = 0.25$ – 0.5 T. Figure 9(a) displays the z torque as a function of the test particle radius (R_2) when gap = 10 nm, and Fig. 9(b) as a function of the gap, with the latter scaled

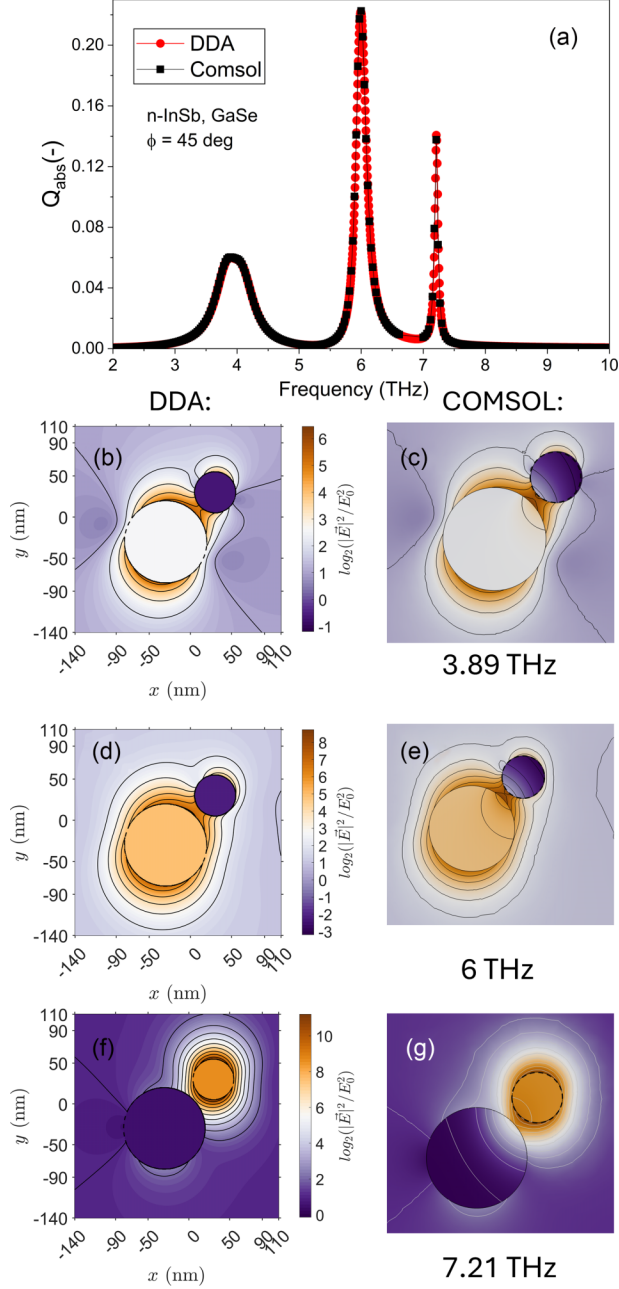


FIG. 7. Electromagnetic response of the $[n\text{-InSb, GaSe}]$ dimer using the coupled-dipole model (DDA) and a comparison against full-wave FEM results (COMSOL). The case corresponds to Fig. 6, evaluated at $\phi = 45^\circ$ as a representative example. (a) Absorption efficiency. (b)–(g) Maps of the relative intensities of the near (electric) field for each resonance visible in the spectrum of panel (a). These colormaps are plotted on a $\log_2$ scale and include isolines for improved visualization of features. Maps in the left [right] column, i.e., (b + d + f) [c + e + g], correspond to DDA [FEM] calculations in the xy plane at $z = 0$. Note the prevailing dipolar-coupling character of the resonances in both methods, especially at low frequencies [panels (b)–(e)]. Higher-order interactions between the particles are also present, as evidenced in maps (c + e + g), but they play a minor role except around the gap region.

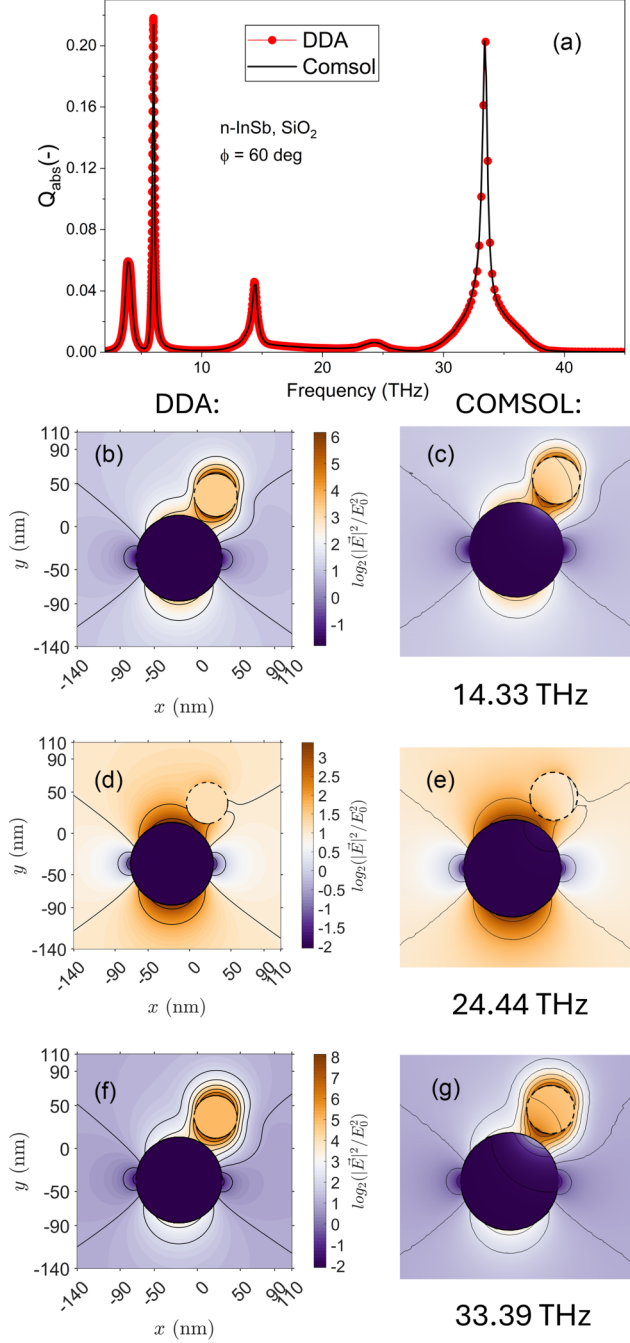


FIG. 8. Electromagnetic response of the $[n\text{-InSb, SiO}_2]$ dimer using the coupled-dipole model (DDA) and a comparison against full-wave FEM results (COMSOL). The case corresponds to Fig. 5, evaluated at $\phi = 60^\circ$ as an arbitrary example. (a) Absorption efficiency. (b)–(d) Maps of the near (electric) field for the three upper-energy resonances visible in the spectrum of panel (a). The figure layout matches that of Fig. 7. Again, the resonance patterns manifest a prevailing dipolar-coupling nature. For the remaining resonances in the spectrum, namely, at 3.89 and 6 THz, the near-field patterns are practically identical to those shown in Figs. 7(b) and 7(c) (not shown here) because they are polariton resonances primarily associated with the $n\text{-InSb}$ particle.

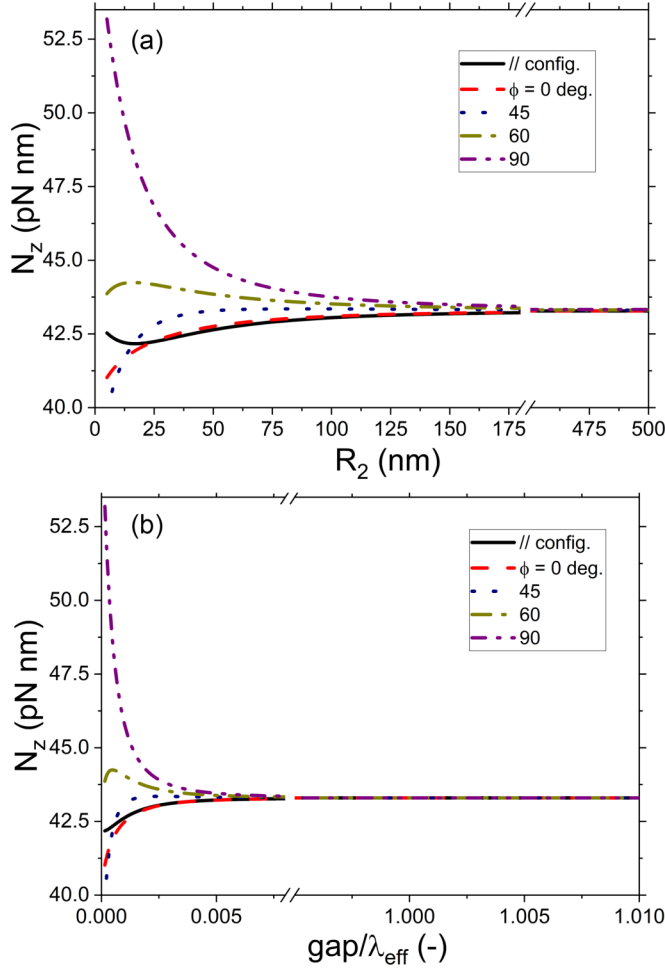


FIG. 9. Example of the variations of the spin torques for the dimer [n -InSb, GaSe] embedded in biomimic, under different configurations for a resonant frequency of 5.93 THz. Particle 1's size is 100 nm. (a) z -Spin torque vs particle 2's radius for a gap of 10 nm; (b) z -spin torque vs gap when $R_2 = 25$ nm. The gap in panel (b) is scaled to the effective wavelength in the outer medium, λ/n_{rb} . Black line corresponds to the configuration of Fig. 1(b). The rest of lines correspond to several dimer angles under perpendicular alignment, as shown schematically in Fig. 1(c).

to the effective wavelength of the system, $\lambda_{\text{eff}} = \lambda/n_{rb}$, when the radius is fixed to $R_2 = 25$ nm. Several configurations were calculated, in particular, one for the parallel illumination [Fig. 1(b)] and four curves for the perpendicular one [Fig. 1(c)]. Remarkably, the strongest variations occur for low values of R_2 [panel (a)] and gap [panel (b)]. As R_2 increases [Fig. 9(a)], the torques reach an asymptotic value that corresponds to the spin torque of the isolated n -InSb particle, since the test particle becomes mechanically unreactive. Similarly, Fig. 9(b) shows the same asymptote because the particles stop interacting as the gap increases. The maxima in both cases are reached at perpendicular configuration for $\phi = 90^\circ$.

One may wonder about the influence of phononic interparticle coupling on the mechanical fingerprints of the system. As the interparticle gap separation decreases, the localized surface polariton modes of the isolated particles undergo near-field electromagnetic mixing, as shown in Figs. 7(b)–7(g) and 8(b)–8(g). Because the spectral phononic lines of the individual constituents are

energetically distinct, this interaction does not represent a direct phononic hybridization. Rather, it constitutes a photonic (electromagnetic) hybridization of the localized surface modes (hybridization of the individual photonic “wave functions”). The overlapping NFs break the spatial symmetry of the isolated systems, lifting the mode degeneracies and redistributing the electromagnetic energy density heavily into the interparticle gap. In general, this field localization alters the Maxwell stress tensor profile, directly driving the observed modifications in the torque spectra compared to those of the isolated particle. By appropriately setting the geometric and constitutive parameters, and taking into account the magnetic field’s magnitude, one could eventually obtain phononic hybridization between the particles, which would lead to the corresponding modification of the mechanical observables.

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