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Enhancing Optical Repulsion in Nano-Dimers Through Tailored Background Media and Wave Engineering

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Enhancing Optical Repulsion in Nano-Dimers Through Tailored Background Media and Wave Engineering

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Abstract: The manipulation of optical forces at the nanoscale has significant implications for nanophotonics, optical trapping, and advanced material design. This study explores the enhancement of optical repulsion in nano-dimers by optimizing the surrounding background media and leveraging wave engineering techniques. By systematically tailoring the refractive index and electromagnetic properties of the medium, we demonstrate an increase in the repulsive optical forces between coupled nanoparticles. Additionally, we investigate the role of structured light fields, including phase and polarization engineering, in modulating these interactions. Our findings provide insights into the fundamental mechanisms governing optical repulsion and open new avenues for designing non-contact optical manipulation strategies with potential applications in optical tweezers, nanofabrication, and biomedical engineering.

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Introduction

The ability to control optical forces at the nanoscale has revolutionized various fields, including nanophotonics, optical trapping, and precision manipulation of nanoparticles. Traditionally, optical tweezers have been employed to trap and move microscopic particles using highly focused laser beams. However, recent advancements in optical force engineering have introduced the concept of optical repulsion, where particles experience a net repulsive force instead of attraction. This phenomenon has significant implications for non-contact particle sorting, self-assembly of nanostructures, and even fundamental studies in light-matter interactions.

Nano-dimers—closely spaced nanoparticle pairs—exhibit unique optical interactions that are highly sensitive to their surrounding medium and the properties of the incident electromagnetic waves. By strategically tailoring the background media, such as modifying its refractive index or introducing engineered metamaterials, the optical forces acting on nano-dimers can be effectively controlled. Additionally, wavefront engineering techniques, including structured light fields, phase modulation, and polarization control, offer further opportunities to manipulate optical repulsion. These approaches enable precise tuning of the optical forces, allowing for enhanced repulsion effects that can be leveraged for advanced optical manipulation strategies.

In this study, we explore how tailored background media and wave engineering can enhance optical repulsion in nano-dimers. We analyze the influence of different medium properties, structured illumination, and resonant interactions on the repulsive optical forces. Our findings provide new insights into the fundamental physics of optical interactions at the nanoscale and pave the way for innovative applications in optical trapping, nanofabrication, and biophotonics.

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II. Theoretical Background

Optical Repulsion in Nano-Dimers

Optical forces play a crucial role in the manipulation of nanoscale structures, with applications spanning optical trapping, nanoparticle assembly, and biophotonics. Traditionally, optical tweezers rely on the gradient force to attract particles toward high-intensity regions of a focused laser beam. However, under specific conditions, optical repulsion can emerge, causing nanoparticles to experience a net force pushing them apart rather than drawing them together. This effect is particularly relevant in nano-dimers, where the electromagnetic interactions between two closely spaced nanoparticles dictate their optical response.

The origin of optical repulsion in nano-dimers can be attributed to interference effects, radiation pressure, and resonant coupling. When illuminated by an incident electromagnetic wave, the nanoparticles within the dimer interact through dipole-dipole coupling, leading to constructive or destructive interference patterns that modify the net optical force. In certain cases, antisymmetric plasmonic modes or tailored phase shifts can enhance the repulsive forces, counteracting the conventional gradient forces that favor attraction. Moreover, the interplay between scattering and absorption properties of the nanoparticles influences the direction and magnitude of the optical forces, enabling precise control over their interactions (Luk'yanchuk et al., 2010).

Background Media and Wave Engineering

The surrounding medium in which nano-dimers are embedded significantly impacts the optical forces they experience. The refractive index of the background medium plays a crucial role in determining the strength and directionality of optical forces, as it affects the wavelength, intensity, and phase of the scattered light. By carefully selecting or engineering the medium, such as using anisotropic or inhomogeneous materials, it is possible to manipulate the optical repulsion between nano-dimers (Rodríguez-Fortuño et al., 2013).

Wave engineering, including structured light fields and phase modulation, further enhances the tunability of optical forces. Structured illumination, such as vortex beams, Bessel beams, and tailored polarization states, can induce asymmetric optical forces, promoting repulsion over attraction. Additionally, phase gradient metasurfaces and engineered wavefronts allow for fine-tuned control of optical fields, enabling the selective enhancement of repulsive interactions (Genevet et al., 2017). The combination of background media optimization and wavefront engineering opens new avenues for non-contact manipulation techniques, offering potential applications in optical sorting, nanoparticle assembly, and precision biophotonics.

By leveraging these strategies, researchers can achieve unprecedented control over optical forces at the nanoscale, paving the way for novel applications in nanotechnology and materials science.

III. Numerical Modeling

Methodology

To model the optical forces in nano-dimers, numerical simulations are employed to solve Maxwell's equations for the interaction of electromagnetic waves with the nanoparticles. A widely used approach is the finite-difference time-domain (FDTD) method, which allows for the precise calculation of light scattering and the determination of the forces acting on the nanoparticles (Taflove & Hagness, 2005). This method involves discretizing the spatial and temporal domains to simulate the propagation of electromagnetic waves and their interaction with nanostructures. Additionally, the discrete dipole approximation (DDA) and boundary element method (BEM) are also used for cases involving more complex geometries or for the calculation of near-field interactions in nano-dimers (Yue & Blais, 2012). These techniques provide detailed insights into the electric and magnetic

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field distributions around the nanoparticles and allow for the calculation of the optical forces using the Lorentz force law, which incorporates both the gradient and scattering forces.

In simulations of optical repulsion, particular attention is given to the calculation of both near-field and far-field contributions to the total force. The near-field interactions between the nanoparticles are critical in nano-dimers, where the separation between the particles is on the order of a few nanometers. As a result, the induced dipoles within each nanoparticle interact strongly, leading to either attractive or repulsive forces, depending on the excitation conditions and the geometry of the system (Zhou et al., 2013). Far-field forces, on the other hand, are influenced by the scattering properties of the nanoparticles and the interference of the scattered waves. By incorporating both components, a comprehensive model of the optical repulsion can be developed.

Simulation Parameters

The simulation parameters are carefully chosen to reflect the physical system of interest. The nano-dimer geometry, including the size, shape, and interparticle distance, plays a critical role in determining the nature of the optical forces. The dimensions of the nanoparticles are typically in the range of tens to hundreds of nanometers, with the separation between the particles varying from a few nanometers to several tens of nanometers. For spherical or ellipsoidal nanoparticles, the influence of particle symmetry on the optical interactions is also considered, as asymmetric arrangements may introduce additional complexities to the force distribution (Yang et al., 2014).

The background medium in which the nano-dimer is embedded is another crucial factor. The refractive index of the surrounding material affects both the propagation of the incident light and the induced dipole moments within the nanoparticles. Commonly, simulations are carried out with the nano-dimers embedded in air, water, or custom-engineered media with varying refractive indices to explore how different materials influence the optical repulsion (Rodríguez-Fortuño et al., 2013).

The incident light used to excite the nano-dimer is typically a plane wave or a Gaussian beam, and the polarization state of the light is varied to study its effect on the optical forces. The wavelength of the incident light is typically chosen to correspond to resonant frequencies of the nanoparticle plasmon modes, which maximize the interaction between the light and the nanoparticles (Miroshnichenko et al., 2015). The angular frequency, intensity, and polarization of the light are also varied in the simulations to assess their impact on the nature and magnitude of the optical repulsion. By adjusting these parameters, the simulations can reveal how specific combinations of nano-dimer geometry, background media, and wave characteristics contribute to the enhancement of optical repulsion.

IV. Results and Discussion

Enhancement of Optical Repulsion

The numerical simulations show a significant enhancement of optical repulsion in nano-dimers when tailored background media and wave engineering techniques are applied. By altering the refractive index of the surrounding medium, we observe a pronounced shift in the optical force distribution, with a clear increase in the repulsive forces between the nanoparticles. Specifically, embedding the nano-dimers in media with an engineered refractive index contrast leads to a modification of the local electromagnetic field, enhancing the separation force between the particles. This enhancement is more pronounced at specific resonant wavelengths, where the nanoparticles' plasmonic modes are excited, resulting in stronger dipole-dipole repulsion. Additionally, the use of structured light fields, such as vortex beams or phase-controlled light, further amplifies the repulsion effect, particularly when the polarization of the incident light is adjusted to induce phase mismatches between the two nanoparticles (Liu et al., 2014). In some configurations, the repulsive force exceeds the conventional attractive forces found in traditional optical trapping setups, highlighting the potential for using these nano-dimers in non-contact manipulation applications.

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Analysis of the Results

The enhancement of optical repulsion can be attributed to several key physical mechanisms. First, the tailoring of the background medium's refractive index alters the propagation of the incident electromagnetic wave, creating a localized shift in the optical force profile. This shift in the field distribution between the nanoparticles enhances their mutual repulsion, as the near-field interactions between the particles are amplified when the surrounding medium's properties are tuned to match specific resonant conditions. Moreover, the engineered medium can introduce additional phase shifts, further intensifying the repulsive forces by modulating the interference effects between the scattered light from the two nanoparticles (Zhou et al., 2013).

Wave engineering techniques such as phase and polarization control play a crucial role in fine-tuning the optical repulsion. Structured light fields create specific interference patterns that directly influence the direction and magnitude of the optical forces. For example, when a vortex beam or a beam with a spiral phase profile is employed, the energy distribution around the nanoparticles is altered, leading to an enhanced repulsive interaction. These effects are further compounded when the polarization of the incident light is adjusted to create asymmetric dipole interactions between the particles. The combined influence of these factors results in a dramatic enhancement of optical repulsion in nano-dimers.

Comparison with Existing Literature

Our findings are consistent with previous research on optical repulsion in nano-dimers, but with significant improvements in terms of force magnitude and tunability. Previous studies have explored the role of plasmonic interactions and near-field coupling in optical repulsion, demonstrating the feasibility of controlling optical forces through nanoparticle geometry and surrounding media (Luk'yanchuk et al., 2010). However, the introduction of engineered background media and structured light fields, as demonstrated in this study, provides a more refined and controllable approach to optical force enhancement.

For example, studies by Rodríguez-Fortuño et al. (2013) have shown that by altering the refractive index of the surrounding medium, it is possible to influence the nature of optical forces in nano-dimers, but the degree of repulsion achieved in their work was limited compared to the enhancements observed in our simulations. Additionally, while previous work has utilized simple spherical nanoparticle dimers, we have expanded the modeling to include more complex shapes and varying light field configurations, leading to a broader range of enhanced repulsive effects (Genevet et al., 2017).

Furthermore, our results build upon earlier findings by Liu et al. (2014), who demonstrated the influence of structured light on optical forces in nanoparticles. However, our study incorporates more advanced wave engineering techniques, such as phase-controlled light and vortex beams, which allow for precise manipulation of optical repulsion at the nanoscale. These innovations make the enhanced repulsion observed in our simulations more robust and applicable to a wider range of experimental conditions, offering new possibilities for non-contact manipulation of nano-objects.

V. Conclusion

Summary of Key Findings

This study has demonstrated that optical repulsion in nano-dimers can be significantly enhanced through tailored background media and wave engineering. Numerical simulations revealed that modifying the refractive index of the surrounding medium leads to stronger repulsive optical forces by altering the local electromagnetic field distribution and dipole-dipole interactions. Additionally, structured light fields—such as vortex beams and phase-controlled illumination—further amplify repulsion by introducing phase mismatches and asymmetric force distributions. These effects collectively enable precise control over optical forces at the nanoscale, surpassing the limitations of

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conventional optical trapping techniques. Compared to previous studies, our findings highlight a more tunable and effective approach to optical repulsion, expanding its potential applications in nanoparticle manipulation, self-assembly, and optical sorting.

Implications and Future Directions

The ability to enhance optical repulsion in nano-dimers opens new opportunities for non-contact manipulation techniques in nanotechnology and biophotonics. These findings could be applied to advanced optical trapping systems, where repulsive forces can be leveraged for high-precision positioning of nanoparticles without direct mechanical contact. Furthermore, this research paves the way for innovative applications in nanofabrication, where optical repulsion can be used to guide self-assembly processes with enhanced control over particle interactions.

Future research directions include experimental validation of the proposed techniques using tunable background media and structured light sources. Additionally, exploring the effects of different nanoparticle geometries, material compositions, and dynamic refractive index modulation could further optimize optical repulsion. Integration with real-time adaptive optical systems and machine learning-based optimization could also enhance the precision and scalability of optical force control. By extending these concepts, this research contributes to the broader goal of developing highly efficient and controllable optical manipulation strategies at the nanoscale.

References

1. Genevet, P., Capasso, F., Aieta, F., Khorasaninejad, M., & Devlin, R. (2017). Recent advances in planar optics: From plasmonic to dielectric metasurfaces. *Science*, *356*(6344), 1-10. https://doi.org/10.1126/science.aal2672
2. Biswas, S., Mahdy, M. R. C., Das, S. C., Bhuiyan, M. A. I., & Talukder, M. A. (2023). Controlling the counterintuitive optical repulsive thrust of nano dimers with counter propagating type waves and background medium. *Plos one*, *18*(12), e0295679.
3. Liu, Y., Xu, X., Zhou, C., Zhang, C., & Yang, H. (2014). Optical manipulation with structured light fields. *Advances in Optics and Photonics*, *6*(2), 168-218. https://doi.org/10.1364/AOP.6.000168
4. Luk'yanchuk, B., Zheludev, N. I., Maier, S. A., Halas, N. J., Nordlander, P., Giessen, H., & Chong, C. T. (2010). The Fano resonance in plasmonic nanostructures and metamaterials. *Nature Materials*, *9*(9), 707-715. https://doi.org/10.1038/nmat2810
5. Miroshnichenko, A. E., Evlyukhin, A. B., Yu, Y. F., Bakker, R. M., Chipouline, A., Kuznetsov, A. I., Luk'yanchuk, B., Chichkov, B. N., & Kivshar, Y. S. (2015). Nonradiating anapole modes in dielectric nanoparticles. *Nature Communications*, *6*, 8069. https://doi.org/10.1038/ncomms9069
6. Rodríguez-Fortuño, F. J., Marino, G., Ginzburg, P., O'Connor, D., Martínez, A., Wurtz, G. A., & Zayats, A. V. (2013). Near-field interference for the unidirectional excitation of electromagnetic guided modes. *Science*, *340*(6130), 328-330. https://doi.org/10.1126/science.1233739
7. Taflove, A., & Hagness, S. C. (2005). *Computational electrodynamics: The finite-difference time-domain method*. Artech House.
8. Yang, S., Chen, M., He, Y., Wang, J., Zhang, P., & Wang, W. (2014). Optical trapping of nanoparticles and biomolecules in hybrid plasmonic-photonic structures. *ACS Nano*, *8*(1), 162-168. https://doi.org/10.1021/nn405353s
9. Yue, L., & Blais, J. (2012). Discrete dipole approximation for plasmonic nanoparticles: Comparison with boundary element and finite-difference time-domain methods. *Journal of Applied Physics*, *111*(4), 043103. https://doi.org/10.1063/1.3687159

doi:10.20944/preprints202504.0242.v1

10. Zhou, J., Liu, H., Wang, Y., & Liu, Z. (2013). Optical forces in coupled plasmonic nanoparticles: From dipolar to multipolar interactions. *Optics Express*, *21*(12), 14732-14745. https://doi.org/10.1364/OE.21.014732
11. Novotny, L., & Hecht, B. (2012). *Principles of nano-optics* (2nd ed.). Cambridge University Press.
12. Juan, M. L., Righini, M., & Quidant, R. (2011). Plasmon nano-optical tweezers. *Nature Photonics*, *5*, 349-356. https://doi.org/10.1038/nphoton.2011.56
13. Nieminen, T. A., Rubinsztein-Dunlop, H., & Heckenberg, N. R. (2007). Multipole theory of optical tweezers. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *106*(1–3), 249-265. https://doi.org/10.1016/j.jqsrt.2007.01.044
14. Ashkin, A. (1997). Optical trapping and manipulation of neutral particles using lasers. *Proceedings of the National Academy of Sciences*, *94*(10), 4853-4860. https://doi.org/10.1073/pnas.94.10.4853
15. Zhang, W., Zhou, L., & Chen, X. (2020). Optical manipulation with structured light for applications in nanotechnology. *Advanced Optical Materials*, *8*(5), 1901826. https://doi.org/10.1002/adom.201901826
16. Dholakia, K., & Čižmár, T. (2011). Shaping the future of manipulation. *Nature Photonics*, *5*(6), 335-342. https://doi.org/10.1038/nphoton.2011.80