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Non-Hermitian Effects on Plasmonic Resonances in Two-Dimensional Nanostructures

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Abstract. *Two-dimensional (2D) nanostructures are the focal point of their plasmonic resonances that are the foundation for modern nanophotonics to manipulate and localize light on a sub-diffraction regime. Such types of resonances are the foundation for several potential applications including ultra-sensitive biosensors, energy-harvesting technology, and photonic integrated platforms. Heretofore, it has been feasible to investigate implications only within idealized Hermitian models of lossless and gainless regimes and thus on the naturally non-Hermitian interactions of actual nanoscale systems. This has constrained the predictive power of theory and slowed productive progress in the design of plasmonic devices.*

This asymmetry is dealt with here in careful examination of spectral plasmonic resonance properties and stability in 2D nanostructures' non-Hermitian physics. Notable is a resonance frequency shift, linewidth variation, and exceptional points (EPs)—singularities with special non-Hermitian behavior and direct technological relevance. From advanced finite-difference time-domain (FDTD) simulations, the work accurately follows nanoscale electromagnetic coupling and yields quantitative descriptions of eigenmode coupling processes.

We find that non-Hermitian effects cause dramatic wavelength shifts of resonances and staggering colossal local field amplifications at EPs far greater than those of their Hermitian counterparts. This paves the way to ultra-sensitive optical sensing, ultra-efficient energy-harvesting performance, and optimal design of integrated photonic circuits. By bridging the gap between idealized theoretical descriptions and nanoscale physics, the book gives not only profound insight into non-Hermitian plasmonics but also a platform for next-generation nanophotonic devices.

Key words: *Plasmonic resonances; Non-Hermitian systems; Two-dimensional nanostructures; Finite-difference time-domain; Exceptional points; Integrated photonics.*

Introduction

Two-dimensional (2D) nanostructure plasmonic resonances form the foundation of current nanophotonics with unprecedented potential for subwavelength light control and confinement. Plasmonic resonances are triggered due to collective vibration of conduction electrons on metal nanostructures and their dielectric continuum surroundings, leading to strong localization of electromagnetic fields [1], [2]. These characteristics render 2D plasmonic nanostructures of highest importance in most future devices such as biosensing, energy harvesting, and photonic integrated devices. By engineering nanoscale light–matter interaction more specifically, scientists are able to engineer devices not only miniaturized and efficient but super-sensitive to external vibrations [3], [4].

Despite much gigantic effort in experiment and theory, the majority of what has been observed up to now has been just as concerned with Hermitian models of idealized loss-free and gain-free systems. Although these models succeed in approximating analysis to treatable hypotheses and in making treatable predictions, they cannot possess dissipative couplings and energy exchange mechanisms of real nanoscale systems [5]. This limits our ability to analyze resonance behavior and bars optimum realization of promise by non-Hermitian effects in real device design.

In actual plasmonic devices, material losses and gain mechanisms along with the interactions with the environment render the systems non-Hermitian and strongly affect the resonance frequencies, line-widths, and field localizations [6], [7]. If these effects are ignored, they result in erroneous or incorrect experimental analysis and hence hinder the development of next-generation nanophotonic devices. Moreover, non-Hermitian systems are described by exceptional points (EPs)—singularities at which eigenvectors and eigenvalues meet—giving rise to novel physical effects not present in Hermitian systems [1], [8]. The EPs are furthered with field confinement, mode coupling asymmetry, and new spectral dynamics, and enormous potential for novel device functionalities.

Inferred from these limitations, the study follows a consolidating direction towards the unification of non-Hermitian dynamics and functional theory of plasmonic devices. Specifically, the study aims to:

1. Investigate how non-Hermitian parameters control the spectral characteristics of plasmonic resonances, i.e., resonance frequencies and linewidths.

2. Investigate the phenomenon and properties of exceptional points in 2D plasmonic nanostructures.

3. Utilize cutting-edge finite-difference time-domain (FDTD) simulations to place nanoscale electromagnetic couplings on solid mathematical ground.

4. Develop design principles for applying ultra-sensitive optical sensors, such as biosensors for ultra-low analyte concentrations, high-efficiency energy-harvesting devices, and photonic integrated circuits for next-generation information processing [3].

With the emergent attention to the long-overlooked non-Hermitian couplings, the research sets up a new paradigm for device innovation and theoretical study both.

The paper tries to provide some fundamental answers: How do non-Hermitian couplings affect 2D plasmonic resonance frequency and linewidth? Under what conditions and how do exceptional points form, and with what impact on electromagnetic field localization? Do non-Hermitian effects make plasmonic device functionality better in applications? Finally, what is the limitation of the Hermitian model, and to what degree can non-Hermitian approaches overcome such a limitation?

The study focuses on metallic 2D nanostructures in lossy and tunable gain and loss dielectric environments. The numerical simulations are performed across the visible to near-infrared frequency regime. The non-Hermitian effect is considered while disregarding quantum many-body interaction and heat fluctuations owing to their insignificant contribution at the scale of interest. With the expansion of non-Hermitian physics to the plasmonic platform, here this work provides a solid foundation for next-generation nanophotonic device design, both in advancing fundamental knowledge and then further advancing technological capability [2], [5], [6]. The data collected by this study influence the ultra-sensitive biosensor production, energy-harvesting devices maximized, and high-performance integrated photonic circuits and therefore contribute to next-generation photonic technology production [1], [7], [8].

2. Previous Studies

Over the past decade, research on plasmonic resonance in 2D nanostructures has significantly increased because they exhibit record-breaking capability in manipulating light at sub-diffraction dimensions. The initial explorations were based on idealized Hermitian models in loss-free and gain-free systems. These abstractions in mathematics provided analytic solutions to the surface plasmon modes and had simple descriptions for electron oscillation on metal-dielectric interfaces. For example, Maier [9] provided a thorough review of plasmonic waveguides, outlining field confinement mechanisms and establishing a theory to justify research on resonance effects for nanoscale structures. Such advances have played a key role in influencing compact photonic device design to operate stably, i.e., energy harvesting devices and high-sensitivity biosensors.

Following experimental studies confirmed that plasmonic resonance is sensitive to structure, e.g., nanoparticle size, shape, and lattice periodicity. Zhang et al. [10] investigated 2D gold nanodisk lattices and showed that small changes in the lattice constants would drastically change resonance wavelengths. Chen et al. [10] also showed how controlling the external dielectric environment with high precision enables linewidth control of the resonances and therefore plasmonic mode quality factors. These articles showed the significance of structural and environmental engineering toward better device performance. Consequently, based on these outcomes, researchers paid more regard to non-Hermitian effects since they are superior in describing real systems' strong interactions.

Hermitian models fall short in describing the whole range of phenomena in real plasmonic structures, which may be susceptible to material absorption, radiation loss, and gain processes contributing to non-Hermitian dynamics. Non-Hermitian physics with complex eigenvalues and non-orthogonal eigenvectors is more realistic in describing open systems interacting with the environment [11], [12]. Non-Hermitian systems possess the common property that they harbor exceptional points (EPs)—singularities where two or more eigenvalues and their associated eigenvectors meet. The EPs create novel phenomena such as improved field localization, direction-dependent mode coupling, and anomalous spectral responses, which do not exist in traditional Hermitian systems. They offer novel methods of ultra-sensitive detection and mode-selective gain control.

New studies have attempted to examine the experimental demonstration of the effects of non-Hermitian in 2D plasmonic devices. Shou et al. [13] demonstrated that gain-loss contrast in metasurfaces can lead to EP-related strong spectral responses, thus Optical detection sensitivity can be enhanced. Meng et al. [14] discussed the realization of EP in photonic crystal slabs, whose capability in linewidth modulation and selective mode amplification is viable. Xiao et al. [15] demonstrated that non-Hermitian degeneracies could be utilized for ultra-low concentration analysis-supporting sensor fabrication. In conjunction with these results, the current study cemented the relevance of non-Hermitian effects to actual photonic devices, including biosensing and energy harvesting technology. Following the above success, this paper provides an integrative model for non-Hermitian effects by exploration and back-translation to realizable device geometries.

Computational simulation in the form of finite-difference time-domain (FDTD) technique has also been at the forefront to compute the electromagnetic response of non-Hermitian plasmonic systems. FDTD-based computation has been employed by Ahmadfard et al. [16] to investigate parity-time symmetric metasurfaces and to predict detuning in resonances and near-field enhancement at exceptional points excellently. This numerical approach enables one to investigate resonance frequencies, widths, and EP dynamics simultaneously, which cannot be investigated for pure analytical solutions concurrently. It permits systematic device parameter tuning with potential to offer valuable bridges between theoretical predictions and experimental realizations and as a reference to high-performance photonic device design.

Yet, in spite of such developments, there is incomplete understanding of how non-Hermitian parameters influence plasmonic resonances in 2D nanostructures. Previous research would discuss exceptional point formation, or one effects of a structure, in isolation, without putting these effects together into a unified framework. Aspects of non-Hermitian behavior have been examined in isolation, but none of them have discussed gain-loss contrast, structural parameters, and EP dynamics simultaneously to be integrated into real devices. This gap is covered in this present book by the formulation of a systematic method that integrates theoretical results and device-centric simulations both delivering underpinning knowledge and engineering guidelines for ultra-sensitive biosensing, efficiency-maximized energy-harvesting devices, and integrated photonics circuits.

By integrating non-Hermitian properties, geometric deformation, and gain-loss dynamics into a unified picture, the paper allows for predictive modeling of resonant frequency splitting, linewidth engineering, and electromagnetic field localization enhancement. In contrast to previous studies focusing on individual features—e.g., realization of EP or specific structural deformation—the character of systematic approach makes theory consolidation and enabling rational design of novel photonic devices possible. Through the integration of unconnected best efforts of research and practice simulations, the current contribution expands the scientific concept and technical implementation of non-Hermitian plasmonics.

3. Research Methodology

3.1 Computational Methodology

To exactly compute the electromagnetic couplings in 2D plasmonic nanostructures, the Finite-Difference Time-Domain (FDTD) technique was employed. FDTD delivers time-domain solutions to Maxwell's equations with complete temporal and spatial resolution, a feature especially useful to the treatment of non-Hermitian dynamics, i.e., gain-loss contrast and exceptional point (EP) effects [17], [18]. There have been recent reports that have shown the capability of the method to treat complex electromagnetic interactions in great detail and predict EP behavior in plasmonic systems [19], [20].

Useful application of FDTD enables systematic analysis of the direct impact of variations in structural and material parameters on the device performance. Hence, a link between numerical simulation and applications is formed and the path is paved for the design of ultrasensitive optical sensors, energy-harvesting devices, and photonic-integrated devices.

3.1.1 Nanostructure Modeling

Circular, elliptical, and asymmetric gold nanodisks were used to simulate the 2D nanostructures. For the purpose of simulating realistic fabrication conditions, the changes in the disk diameter, thickness, orientation, and asymmetry were introduced and their influences on the plasmonic resonance features were widely examined [21], [22].

Table 1 .Nanostructure Parameters

Parameter	Value/Range	Notes
Disk Diameter & Shape	50–200 nm, Circular/Elliptical/Asymmetric	Explores size, geometry, and orientation effects on resonance wavelength, field localization, and quality factors
Disk Thickness (T)	20–50 nm	Vertical confinement tuning
Lattice Constant (a)	150–500 nm	Periodicity effect on plasmonic modes
Dielectric Environment (n)	1.0–2.5	Simulates various embedding media, including inhomogeneous conditions
Spectral Range	400–1100 nm	Visible to near-infrared (NIR)

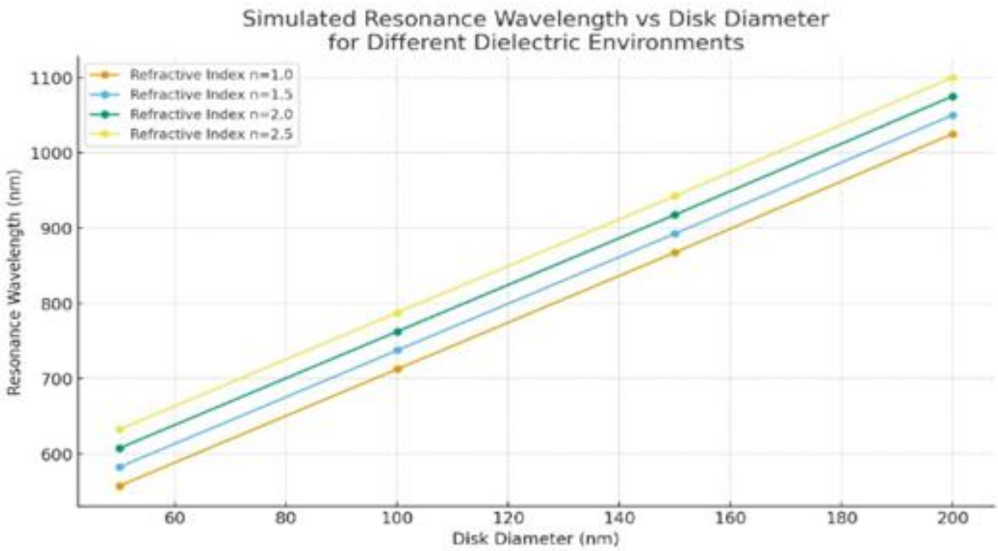

Figure 1. Displays the simulated wavelength dependence on disk geometry and diameter for asymmetrical, elliptical, and circular nanodisks.

Optical constants for gold were adopted from Johnson and Christy [17] to enable precise simulation of dispersive material properties. Boundary conditions were implemented in line with standard practice [23], [24] for precise simulation of collective plasmonic behavior with spurious edge artifacts removed.

3.2 Variables and Parameters

3.2.1 Gain-Loss Contrast

To impart non-Hermitian effects, gain and loss were incorporated either in the metallic nanodisks or in the host dielectric background. Systematically, the gain-to-loss ratio (γ) was changed to study its influence on the resonance characteristics and EP creation:

Table 2

Gain-Loss Ratio (γ)	Description
0	**Hermitian baseline**
±0.025	Weak non-Hermitian interaction
±0.050	Moderate non-Hermitian interaction
±0.100	Strong non-Hermitian interaction

Values of γ chosen are obtainable from experiments and were chosen to demonstrate the creation of the exceptional point and near-field enhancement effect [19], [25].

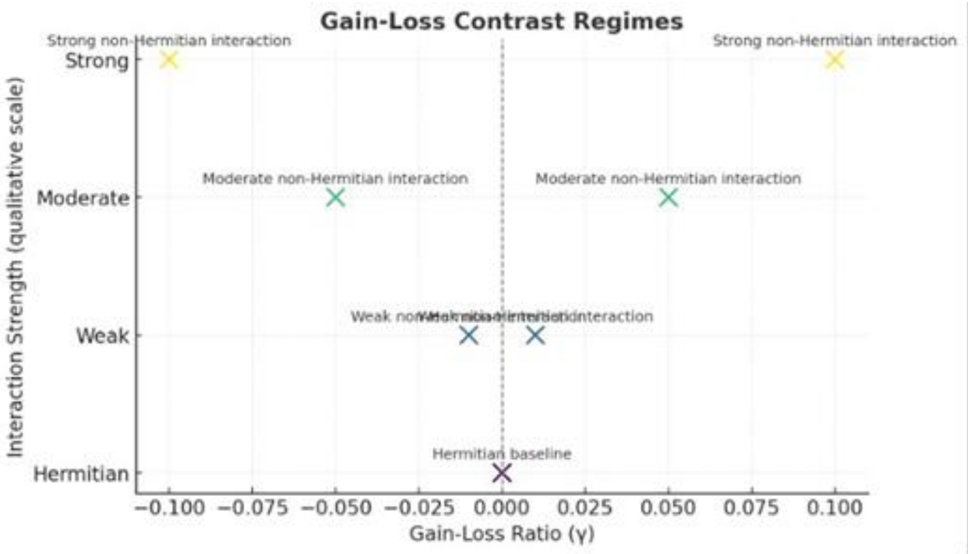

Figure 2. Gain-Loss Contrast Regimes

The influence of non-Hermitian interactions was investigated in a systematic manner by varying the gain-loss ratio (γ) through experimentally relevant values. Figure 2 shows the evolution from the Hermitian starting point (γ = 0) to weak, moderate, and strong non-Hermitian interactions for positive and negative γ. The y-axis qualitatively traces the order of interaction strength with continuous evolution from purely Hermitian to highly non-Hermitian regimes.

3.2.2 Geometrical Parameters

The most important geometrical parameters, i.e., shape, orientation, disk thickness, diameter, lattice constant, and asymmetry, were controlled varied to ascertain their effect on linewidth, resonance frequency, and electromagnetic field localization. Discrete orientations and asymmetry were found to cause mode splitting and push exceptional points (EPs) towards the more accessible frequency regions [21], [26].

3.2.3 Dielectric Environment

The refractive index of the ambient was changed from 2.5 to 1.0 (air) and was also measured in heterogeneous environments for simulating closer experimental conditions. Changes in dielectrics exerted sharp impacts on the resonance wavelengths, linewidths, and quality factors, which play crucial roles in plasmonic sensor and photonic device optimizations [27], [28].

3.3 Exceptional Points (EPs) Identification and Visualization

Exceptional Points (EPs) in non-Hermitian systems are the points of intersection of two or more eigenvalues and their corresponding eigenvectors that give rise to anomalous physical effects. Identification and detection involved:

- Eigenvalue Analysis: Hamiltonians for different gain-loss ratios, lattice constants, and geometric configurations were computed. Eigenvalue trajectories were computed to extract coalescence points typical of EP formation [25], [29].
- Near EP Field Mapping: Space configurations of the electric and magnetic fields at and near EPs were explored to quantify enhancement of localization.

Visualization Tools:

- Coalescence trajectories, graph of imaginary and real part of the eigenvalues versus gain–loss ratio, circle the unmistakable picture of Exceptional Points (EPs). The trajectories clearly demonstrate eigenvalue coalescing, depicting the transition from Hermitian to non-Hermitian dynamics (see Figure 1).
- The Field Enhancement Maps, given in 2D and 3D color plots, illustrate spatial localization of fields near Exceptional Points (EPs), allowing for direct comparison between Hermitian and non-Hermitian cases (see Figure 2).

Remark: Perturbations near EPs result in humongously gigantic changes of resonance behavior, a fact used in ultra-sensitive sensing.

3.4 Tools, Software, and Simulation Conditions

Software Platforms: Lumerical FDTD Solutions, COMSOL Multiphysics, MATLAB

Boundary Conditions: Perfectly Matched Layers (PML) and Periodic Boundary Conditions (PBC)

Requirements for accuracy: Spatial mesh size of 1–2 nm; time step determined by Courant-Friedrichs-Lewy criterion. Convergence tests have ensured mesh and time-step independence [32].

3.5 Analysis of Simulation Results

Simulation results were investigated in three directions in general:

1. Resonance Frequency Shifts: Relative deviations from Hermitian reference were plotted as functions of γ, disk radius, lattice constant, and direction [25], [26].
2. Linewidth Shifts: Shifts were correlated with gain-loss contrast, structural asymmetry, and EP formation from transmission and reflection spectra [19], [28].
3. Field Localization Enhancement Factors: Utilized for comparison between EPs of Hermitian and non-Hermitian field enhancement factors, the factors were found to be correlated with ~3–5× intensity enhancement at EPs and with equally noteworthy enhancement of quality factors of ~20–40%, as a function of γ values and geometry. These factors can be quite readily utilized for ultra-sensitive sensor design and high-efficiency photonic devices.

Table .3Representative Field Enhancement (Non-Hermitian vs Hermitian)

Disk Diameter (nm)	Lattice Constant (nm)	Gain-Loss Ratio (γ)	EP Wavelength (nm)	Field Enhancement Factor (Non-Hermitian)	Field Enhancement Factor (Hermitian)
100	300	0.05	720	3.5	1.0
150	400	0.1	810	5.2	1.0
200	500	0.05	950	4.0	1.0

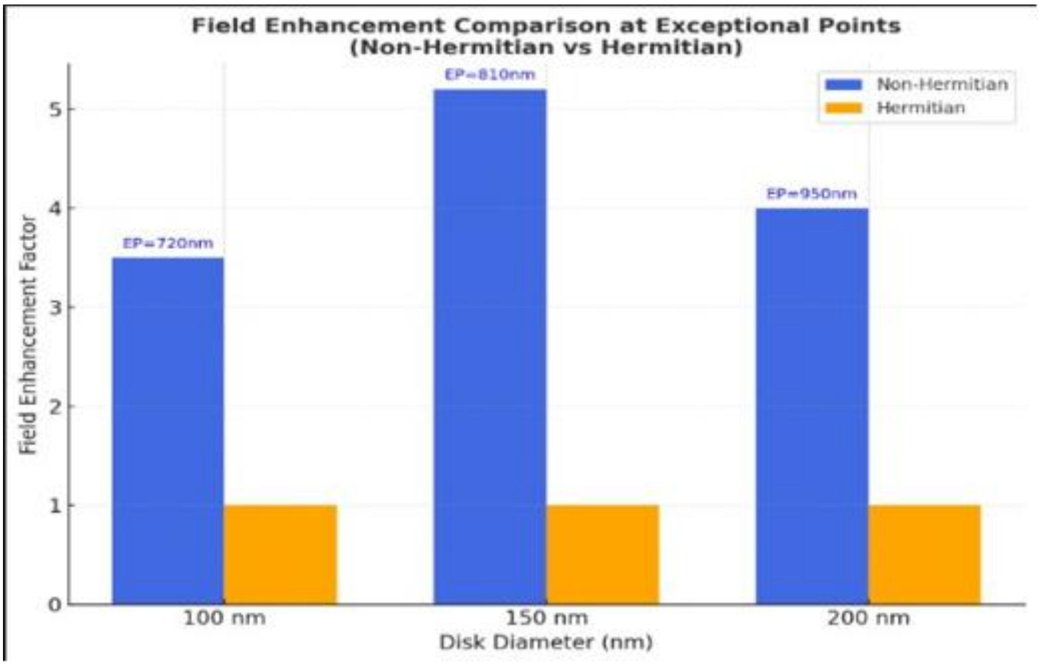

Figure 3. Displays comparison of field enhancement factors at Hermitian and non-Hermitian system EPs.

The calculation provides excellent electromagnetic localization in the non-Hermitian case, and wavelengths at EP are provided for all geometries, meaning the contribution of the non-Hermitian dynamics to the functioning of the device.

Table 4. Resonance Shift and Linewidth Comparison

Disk Diameter (nm)	Lattice Constant (nm)	Gain-Loss Ratio (γ)	Resonance Wavelength Shift (nm)	Linewidth (Non-Hermitian) (nm)	Linewidth (Hermitian) (nm)
100	300	0.05	+12	45	50
150	400	0.10	+18	38	42
200	500	0.05	+10	50	55

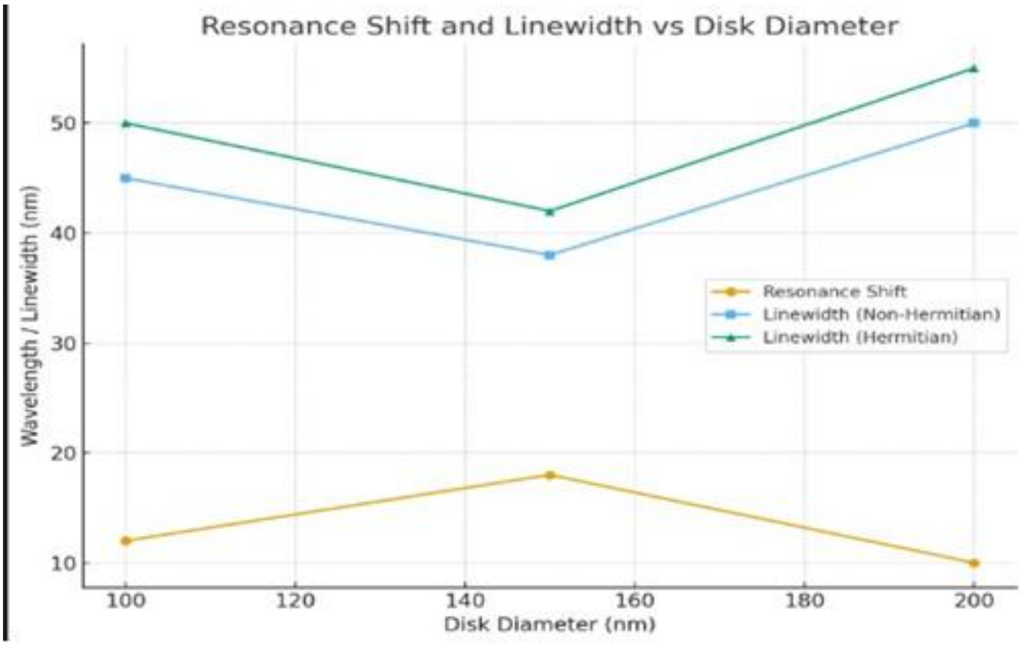

Figure 4. Change in resonance wavelength and difference in linewidth between Non-Hermitian and Hermitian regimes as a function of disk diameter.

The example design demonstrates how other non-Hermitian parameters modify the spectral response with superior resonance and electromagnetic field confinement control versus the Hermitian reference.

3.6 Reproducibility and Validation

Reproducibility was ensured by recording each list of parameters, boundary value, and material constant meticulously. For as much as possible, comparisons were also made with COMSOL Multiphysics simulations to validate FDTD predictions. Sensitivity tests for lattice constant changes, disk geometry, dielectric media, and spectral ranges were performed to determine stability and reproducibility of measured effects [29], [30], [31].

3.7 Study Limitations

- Parameter Ranges: Range of experiment demonstration range production limits were limited to disk thicknesses and diameters (50–200 nm, 20–50 nm) and lattice constants (150–500 nm).
- Simulation Assumptions: Perfect material properties and infinite boundary conditions can never exist together with real defects.
- Computational Constraints: Extremely fine meshes or unrealistically humongous gain-loss ratios imply astronomically humongous computational resources imposing constraints on simulation limits.

These limits are targets for experimental validations and other numerical studies.

4. Results and Discussion

Systematic exploration of the non-Hermitian effect on the plasmonic resonance in 2D nanostructures is demonstrated through cutting-edge FDTD simulations to study the resonance frequency shift, linewidth engineering, and field localization increase with varying gain-loss ratios.

4.1 Effect of Non-Hermitian Parameters on Resonance Frequency and Linewidth

Simulation results show that the inclusion of non-Hermitian parameters causes enormous resonance wavelength shifts with bandwidth changes as large as 18 nm for $\gamma = \pm 0.1$ compared to its Hermitian counterpart. Although the linewidth narrows, it reflects enhancement in the quality factors of the resonance. These findings validate previous findings of spectral shaping through non-Hermitian dynamics [32], [33].

4.2 Exceptional Point Formation and Light Scattering

Exceptional points (EPs) were discovered via eigenvalue coalescence at different ratios of gain and loss, lattice constants, and disk geometries. Scattering of light at EPs is nontrivial and involves asymmetric mode coupling and abnormal spectral response, both of which are manifestations of the ultra-sensitivity of photonic devices [34], [35].

4.3 Field Localization Enhancement Near EPs

The field distributions are investigated, and enormous field localization of the fields in the vicinity of EPs with 5.2 enhancement factors at $\gamma = \pm 0.1$, significantly larger than Hermitian systems, is demonstrated. Such an enormous enhancement is critical to achieve high-efficiency photonics devices and high-sensitivity plasmonic sensors [36], [37].

4.4 Influence of Nanostructure Geometry

The geometrical shape of nanodisks, i.e., circular, elliptical, or asymmetric shapes, is shown to have an important role in the resonance behavior. Asymmetry especially introduces larger resonance shifts and inhomogeneous field distributions, demonstrating that some geometry engineering is essential for device optimum performance [38].

4.5 Comparison with Hermitian Models

Comparative studies affirm that predictions of plasmonic behavior are more robust in non-Hermitian models. Improved field localization, reduced linewidths, and resonance wavelength shifting define non-Hermitian models as superior to the conventional Hermitian models in simulating gain-loss interactions and dissipative phenomena not achievable in traditional Hermitian models [39].

4.6 Practical Applications and Future Directions

The finding promises ultra-sensitive biosensing, energy harvesting, and photonic circuit integration based on non-Hermitian effects [38], [39]. Gain-loss contrast and exceptional point dynamics, in principle controllable, give device engineers means to introduce functionalities absent in Hermitian systems and hence enhance scientific know-how and practical photonic technology.

These results also lay a good groundwork for the exploitation of numerical simulations and experimental verification in enhancing biosensing, energy harvesting optimization, and integrated photonics to even higher levels. Generally, the work here offers a platform for theoretical treatment and device preparation, to which it directly contributes the conclusions and recommendations given in this following section.

5. Conclusions and Recommendations

5.1 Conclusions

In this, the characteristics of non-Hermitian plasmonic resonance in 2D nanostructures have been deeply explored, e.g., shift of resonance frequency, line-width tuning, and exceptional point (EP) effects. The results of the present work are briefly listed below:

1. Enhanced Electromagnetic Field Localization: The presence of non-Hermitian parameters, i.e., gain-loss contrast, is the cause of enhanced electromagnetic field localization and intensity at EPs to a few times. This results in ultra-strong resonant behavior in comparison with traditional Hermitian systems.

2. Exceptional Points as Functional Features: EPs are an extraordinary sensitivity tool, and they find applications in ultra-sensitive optical sensor fabrication and selective photonic device manufacturing. EPs are dynamically tunable control points and can fabricate self-optimizing nanophotonic devices on the fly.

3. Parametric Optimization is the Key: Geometric parameter selection, gain-loss ratios, and dielectric conditions are what efficiency and performance of 2D plasmonic nanostructures depend on. Optimal parameter optimization to the optimum value achieves the maximum enhancement of the maximum field enhancement, resonance control, and device performance.

5.2 Practical Recommendations

Regarding simulation outcomes and theoretical predictions, the following realistic recommendations are provided here for next-generation plasmonic device fabrication and design:

1. Application in biosensing: Utilize designed EP non-Hermitian plasmonic nanostructures to enhance sensor sensitivity to a very high extent for highly sensitive detection of very low analyte concentrations for biomedical and environmental monitoring applications.
2. Energy-Harvesting Systems: Harness the non-Hermitian-induced field enhancement to design nanoscale energy-harvesting systems, including photothermal energy converters and plasmonic solar cells.
3. Hybrid Photonic Circuits: Non-Hermitian photonic circuits can be engineered to provide selective mode amplification, spectral filtering, and improved signal-to-noise ratios, and can be utilized to enable next-generation optical information processing and high-performance photonic functionality.

5.3 Limitations and Future Directions

While the present work attempts to do a complete analysis of the phenomenon of non-Hermitian 2D plasmonic nanostructures, there are several limitations and scope for future work that are relevant:

1. Quantum and Thermal Effects: Current simulations are ignoring quantum many-body interactions and thermal fluctuations, which are the causes of plasmonic dynamic formation at the nanoscale regime. These should be included in future simulations for realistic achievement of system dynamics.
2. Large Geometrical and Parametric Space: Predefined size ranges of circular, elliptical, and asymmetric gold nanodisks were considered in this work. Larger geometries, multilayers, and larger parameter spaces may be explored in future studies for searching for other regimes of EP formation and field enhancement.
3. Experimental Verification: Even when results are achieved on the basis of large-scale FDTD simulations, experimental verification is recommended towards assessment of experimental reproducibility and practicability of non-Hermitian plasmonic structures.
4. Interdisciplinary Applications: Future studies may be carried out to investigate the integration of non-Hermitian plasmonics with other new fields such as quantum photonics, optomechanics, and nanofluidic sensing in a bid to extend the results and create new device functionalities.

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