Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Geometry-Controlled Plasmonic Localization and Graphene-Assisted Thermal Redistribution in Hybrid Gold–Graphene Nanocylinder Arrays

Mohammad Sadegh Akhoundi Khezrabad
ms_akhoundi@pnu.ac.ir

Payame Noor University

Samira Zolfaghari Nikanjam
Payame Noor University

Research Article

Keywords: Localized surface plasmon resonance (LSPR), Hybrid gold–graphene nanostructures, Aspect-ratio engineering, Plasmonic energy localization, Thermal redistribution, Thermoplasmonics, Optical–thermal stability

Posted Date: July 14th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10081831/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Localized plasmonic nanostructures provide an effective platform for concentrating electromagnetic energy into subwavelength volumes, enabling enhanced light–matter interaction and localized photothermal generation. In this work, a hybrid nanophotonic structure consisting of ordered arrays of gold nanocylinders integrated with a graphene layer on a SiO_2 substrate is investigated using finite-difference time-domain (FDTD) simulations coupled with thermal analysis. The study systematically examines the influence of nanocylinder aspect ratio on plasmon resonance characteristics, electromagnetic near-field localization, and photothermal energy redistribution.

The results demonstrate that increasing the height-to-radius ratio enhances plasmonic energy localization, strengthens near-field confinement, and increases optical absorption through the formation of highly localized plasmonic hot spots. Comparative analysis of graphene-free and graphene-coupled configurations reveals that graphene substantially modifies the resulting thermal response owing to its exceptionally high in-plane thermal conductivity. While plasmon-induced heat generation remains concentrated near the optical hot spots, graphene promotes rapid lateral heat diffusion, suppresses excessive thermal localization, and produces a significantly more uniform temperature distribution.

Quantitative analysis shows that the incorporation of graphene reduces temperature non-uniformity by approximately 92.5% while preserving strong plasmonic enhancement. The corresponding optical–thermal stability factor increases by more than one order of magnitude, demonstrating the effectiveness of graphene-assisted thermal management. These findings show that aspect-ratio engineering and graphene-assisted heat spreading perform complementary functions: the former governs plasmonic energy localization, whereas the latter regulates thermal energy redistribution. The proposed hybrid architecture establishes an integrated optical–thermal design framework for achieving simultaneous optical enhancement and thermal stabilization in plasmonic nanophotonic systems.

1.Introduction

Controlling electromagnetic energy at the nanoscale is a central objective in plasmonic nanophotonics. Metallic nanostructures based on noble metals such as gold can support localized surface plasmon resonances (LSPRs), which arise from the collective oscillation of conduction electrons under optical excitation and enable strong confinement of electromagnetic fields within subwavelength volumes [1, 2]. Such nanoscale field confinement provides an efficient route for enhancing light–matter interaction, concentrating optical energy near metal surfaces, and converting absorbed electromagnetic energy into localized heat [3, 4].

A key feature of localized plasmonic systems is the strong dependence of their optical response on structural geometry. In anisotropic metallic nanostructures, including nanorods and nanocylinders, the aspect ratio provides an effective parameter for tuning plasmonic resonance conditions. Increasing the characteristic dimension of the metallic structure along the electron oscillation direction modifies the restoring force acting on the electron cloud and shifts the plasmon resonance toward longer wavelengths. This geometry-dependent behavior has been extensively reported for anisotropic metallic nanostructures, where particle shape and aspect ratio strongly influence resonance wavelength, scattering efficiency, and photothermal response [1, 5–8].

Therefore, aspect-ratio engineering offers a material-independent strategy for controlling plasmonic resonance, electromagnetic near-field localization, and nanoscale energy confinement.

In parallel, graphene has emerged as an important two-dimensional material for hybrid plasmonic platforms owing to its broadband optical response, high electrical conductivity, and exceptionally **high in-plane thermal conductivity** [9–11]. Although monolayer graphene absorbs only a small fraction of incident visible light, approximately 2.3%, its interaction with localized electromagnetic fields can be significantly strengthened when coupled to plasmonic nanostructures [12, 13]. In such hybrid metal–graphene systems, plasmon-induced near fields provide a mechanism for concentrating electromagnetic energy at the graphene interface, while graphene can simultaneously act as a lateral pathway for thermal energy redistribution.

Hybrid plasmonic–graphene structures have been widely investigated for enhanced optical absorption, photocarrier generation, and modified light–matter interaction [14–17]. However, many previous studies have focused mainly on optical enhancement or device-oriented performance, while the spatial relationship between plasmonic energy localization and the resulting thermal redistribution has received less systematic attention. In particular, for ordered nanocylinder arrays, the way in which a single geometric parameter, such as aspect ratio, simultaneously controls resonance tuning, near-field confinement, and graphene-assisted heat spreading remains insufficiently clarified.

Recent advances in hybrid plasmonic platforms have demonstrated significant improvements in optical confinement, sensing performance, and light–matter interaction, while thermoplasmonic and hot-carrier studies have revealed a strong interplay between plasmonic localization and thermal energy redistribution, highlighting the need for integrated optical–thermal analyses in hybrid nanostructures [18–22].

Here, we investigate a hybrid gold–graphene nanophotonic platform consisting of ordered arrays of gold nanocylinders placed on a graphene layer supported by a SiO_2 substrate. Using finite-difference time-domain (FDTD) simulations combined with thermal analysis, we examine how the height-to-radius ratio of the gold nanocylinders governs plasmonic energy localization. The study focuses on three connected physical responses: spectral plasmon resonance tuning, near-field electromagnetic confinement, and photothermal energy redistribution. By comparing graphene-coupled and graphene-free configurations, we clarify the role of graphene not merely as an optical interface but as a functional thermal redistribution layer that moderates plasmon-induced localized heating.

Unlike previous studies that primarily focused on optical enhancement, absorption improvement, or device-specific performance, the present work investigates the coupled optical–thermal behavior of hybrid gold–graphene nanocylinder arrays from an energy-localization perspective. We demonstrate

that aspect-ratio engineering enhances plasmonic energy localization, while graphene-assisted heat spreading suppresses excessive thermal localization, enabling simultaneous optical enhancement and thermal stabilization. This establishes a unified framework linking plasmon resonance tuning, near-field confinement, and thermal management in hybrid plasmonic nanostructures.

The remainder of this paper is organized as follows. Section 2 presents the physical framework underlying plasmonic localization and thermal redistribution. Section 3 describes the structural design and numerical simulation methodology. Section 4 discusses the optical, electromagnetic, and thermal responses of the proposed hybrid nanostructure and introduces quantitative optical–thermal stability metrics. Finally, Section 5 summarizes the main findings and conclusions.

2. Physical Framework of Plasmonic Localization and Thermal Redistribution

Localized surface plasmon resonances (LSPRs) originate from the collective oscillation of conduction electrons in metallic nanostructures under electromagnetic excitation. In gold nanocylinders, the incident optical field drives the free electrons, producing localized charge oscillations at the metal surface. These oscillations confine electromagnetic energy into nanoscale regions near the nanocylinder boundaries, thereby forming plasmonic hot spots and enabling strong near-field energy localization. Recent studies have highlighted the importance of such plasmon-mediated optical processes for enhancing light confinement and energy localization in nanophotonic devices [23].

The resonance condition of a localized plasmon is governed by the geometry of the nanostructure and the dielectric environment surrounding it. For anisotropic nanostructures such as nanocylinders, the aspect ratio controls the effective electron oscillation length. Increasing the height-to-radius ratio elongates the oscillation pathway of conduction electrons and reduces the restoring force acting on the induced charge distribution. As a result, the plasmon resonance shifts toward longer wavelengths. This qualitative dependence can be expressed as:

$$\lambda_{res} \propto L_{eff}$$

where L_{eff} denotes the effective oscillation length associated with the dominant plasmonic mode. For the present gold nanocylinder geometry, increasing the cylinder height while keeping the radius fixed increases L_{eff}, leading to the observed red shift of the plasmonic resonance.

The spatial localization of plasmonic energy can be described by the electric-field intensity distribution:

$$|E(r)|^2$$

Regions with enhanced $|E|^2$ correspond to plasmonic hot spots, where electromagnetic energy is concentrated near the nanocylinder edges and at the metal–graphene interface. In the present structure, the nanocylinder geometry controls not only the spectral position of the resonance but also the spatial distribution of near-field energy localization.

Plasmonic energy localization is directly connected to photothermal generation. When electromagnetic energy is absorbed inside the gold nanocylinders, it is converted into heat through dissipative electron–phonon processes. The local volumetric heat generation rate can be written as:

$$Q(r) = \frac{1}{2}\omega\varepsilon_0\varepsilon''|E(r)|^2$$

where ω is the angular frequency of the incident light, ε_0 is the vacuum permittivity, ε" is the imaginary part of the dielectric function of gold, and E(r) is the local electric-field amplitude. This relation indicates that the regions of stronger near-field localization are also the regions of stronger photothermal energy generation. The conversion of localized electromagnetic energy into heat through non-radiative plasmon decay is the fundamental mechanism underlying thermoplasmonic phenomena. Previous studies have demonstrated that regions exhibiting strong near-field enhancement also act as localized nanoscale heat sources, leading to highly confined temperature distributions around metallic nanostructures [24, 25].

In the hybrid gold–graphene structure, graphene modifies the thermal response of the system through its exceptionally high in-plane thermal conductivity, which can exceed several thousand W m − 1 K − 1 under suitable conditions. Such thermal transport characteristics enable efficient lateral heat spreading and have motivated the use of graphene as a thermal management material in nanoscale optoelectronic and plasmonic systems [26, 27]. While the gold nanocylinders act as plasmonic energy concentrators, the graphene layer provides a lateral pathway for redistributing the generated heat. Therefore, graphene does not merely serve as a passive optical interface; rather, it functions as a thermal redistribution layer that mitigates excessive temperature accumulation near plasmonic hot spots.

Therefore, the physical behavior of the proposed hybrid nanostructure can be understood as a coupled geometry-controlled process. The nanocylinder aspect ratio determines the plasmonic resonance condition and near-field energy localization, while the graphene layer regulates the spatial redistribution of the generated heat. This framework provides the physical basis for interpreting the optical absorption spectra, near-field maps, and thermal distributions discussed in the following sections.

3. Materials and Methods

3.1 Structural Design of the Hybrid Nanophotonic Platform

The investigated nanophotonic structure consists of a hybrid platform composed of a SiO_2 dielectric substrate, a graphene layer, and an ordered array of gold nanocylinders. The SiO_2 substrate with a thickness of 80 nm serves as the dielectric support for the structure. A three-layer graphene sheet with an

effective thickness of 0.1nm (thickness of a monolayer graphen is 0.03nm) is placed on top of the substrate and acts as an optoelectronic interface as well as a thermal dissipation layer. The schematic structure of the simulated hybrid nanophotonic platform, consisting of gold nanocylinders positioned on a graphene layer supported by a SiO_2 substrate, is illustrated in Fig. 1.

The plasmonic component of the structure consists of an array of gold nanocylinders arranged in a 4 × 5 configuration on the graphene layer. The diameter of the nanocylinders is kept constant while the aspect ratio, defined as the height-to-radius ratio (h/R), is used as the main geometric control parameter. Three aspect-ratio configurations are considered in this study: h/R = 1, h/R = 2, and h/R = 3. This parametric variation enables systematic investigation of the influence of geometric engineering on plasmonic resonance behavior, electromagnetic near-field localization, and photothermal energy distribution within the hybrid system.

To clarify the physical role of graphene in the thermal response of the structure, comparative simulations were additionally performed for graphene-free configurations. This comparison enables direct evaluation of how graphene modifies plasmon-induced thermal localization and heat redistribution within the hybrid nanostructure.

3.2 Optical Material Models

The optical properties of gold are modeled using experimentally measured dielectric constants reported by Johnson and Christy, which are widely used in plasmonic simulations. Graphene is modeled as a two-dimensional conductive layer characterized by its surface conductivity and intrinsic optical absorption of approximately 2.3% in the visible spectral range[28]. The SiO_2 substrate is modeled as a dielectric material with a constant refractive index within the considered wavelength range.

3.3 Numerical Simulation Framework

Optical simulations are performed using the finite-difference time-domain (FDTD) method implemented in the Lumerical FDTD Solutions software package. A linearly polarized plane wave is used as the excitation source and propagates along the z-direction toward the nanostructure array. The wavelength range of the incident light is chosen between 400 nm and 900 nm in order to cover the visible and near-infrared spectral regions.

Periodic boundary conditions are applied along the x and y directions to represent the periodic nature of the nanostructure array, while perfectly matched layer (PML) boundaries are implemented along the z-direction to suppress artificial reflections from the simulation domain boundaries.

A nonuniform spatial mesh is employed to ensure numerical accuracy. In regions close to the gold nanocylinders and the graphene layer, a finer mesh is used in order to accurately resolve the strong electromagnetic field gradients associated with plasmonic resonances.

3.4 Optical Absorption and Near-Field Analysis

The optical absorption spectrum of the hybrid structure is calculated using the relation

$$A(\lambda) = 1 - R(\lambda) - T(\lambda)$$

where $R(\lambda)$ and $T(\lambda)$ represent the wavelength-dependent reflection and transmission coefficients, respectively.

To investigate plasmon-induced field enhancement, spatial distributions of the electric field intensity are extracted in both x–y and x–z planes. These near-field maps enable identification of localized electromagnetic hot spots and provide insights into the coupling between plasmonic nanocylinders and the graphene layer.

3.5 Photothermal Modeling

The photothermal response of the structure is evaluated by computing the volumetric heat generation resulting from electromagnetic absorption in the plasmonic nanostructures. The calculated volumetric heat generation term described in Section 2 was subsequently incorporated into the thermal solver for evaluation of the steady-state temperature distribution within the nanostructure.

The thermal conductivity of graphene was incorporated into the model in order to account for heat transport within the hybrid structure. Two-dimensional and three-dimensional temperature distributions were calculated to analyze the photothermal response of the hybrid nanostructure.

4. Results and Discussion

4.1 Geometry-Dependent Plasmon Resonance

To establish a reference for evaluating the influence of graphene on the optical response of the proposed structure, the plasmonic absorption spectra of gold nanocylinder arrays without the graphene layer were first investigated for three different aspect-ratio configurations (h/R = 1, 2, and 3), as shown in Fig. 2.

Figure 2 presents the absorption spectra of gold nanocylinder arrays without the graphene layer for three aspect-ratio configurations. The results show that increasing the aspect ratio substantially enhances the absorption intensity of the dominant plasmonic mode. The maximum absorption increases from approximately 2.9 a.u. for h/R = 1 to about 5.0 a.u. for h/R = 2 and reaches nearly 5.8 a.u. for h/R = 3. Simultaneously, the spectra become increasingly structured, exhibiting multiple secondary resonances and stronger oscillatory behavior at higher aspect ratios. These observations indicate that increasing

the nanocylinder height strengthens plasmonic excitation and promotes the excitation of additional resonant modes, leading to enhanced optical energy localization within the metallic nanostructure.

To examine the role of graphene in modifying the plasmonic response, the absorption spectra of the corresponding graphene-coupled hybrid structures were subsequently calculated and are presented in Fig. 3.

Figure 3 shows the corresponding absorption spectra of the graphene-coupled hybrid nanostructures. Similar to the graphene-free case, increasing the aspect ratio leads to a pronounced increase in absorption intensity, with the dominant peak rising from approximately 2.7 a.u. for h/R = 1 to about 5.5 a.u. for h/R = 2 and nearly 6.6 a.u. for h/R = 3. However, in contrast to the graphene-free configuration, the resonance profiles become noticeably smoother and exhibit reduced oscillatory features. The presence of graphene therefore preserves the strong plasmonic enhancement associated with larger aspect ratios while simultaneously modifying the spectral response of the structure. This behavior suggests that graphene affects the distribution and coupling of localized electromagnetic modes at the metal–graphene interface.

A direct comparison between Figs. 2 and 3 demonstrates that the nanocylinder aspect ratio is the primary parameter governing the strength of plasmonic excitation and optical energy localization, whereas graphene mainly influences the spectral manifestation of these resonances. While both structures exhibit a significant increase in absorption with increasing h/R, the graphene-coupled configurations display smoother spectral profiles and reduced resonance oscillations. These results indicate that aspect-ratio engineering enhances plasmonic energy localization, whereas graphene modifies the optical response through mode redistribution at the interface. To further investigate the spatial distribution of the localized electromagnetic energy responsible for the observed absorption behavior, the near-field electric-field distributions are examined in the following section.

To clarify the physical origin of the enhanced optical absorption observed in the graphene-coupled hybrid structure, the spatial distributions of the electric-field intensity were analyzed for different nanocylinder aspect ratios.

Figure 4 shows the normalized electric-field intensity distributions in the x–y plane for h/R = 1, 2, and 3. A progressive increase in near-field localization is clearly observed with increasing aspect ratio. The maximum normalized field intensity increases from approximately 0.16 for h/R = 1 to about 0.185 for h/R = 2 and reaches nearly 0.256 for h/R = 3. Simultaneously, the electromagnetic energy becomes increasingly confined near the nanocylinder boundaries, leading to the formation of pronounced plasmonic hot spots. These results demonstrate that larger aspect ratios enhance electromagnetic confinement and concentrate optical energy into progressively smaller nanoscale regions, therefore explaining the enhanced absorption behavior observed in the hybrid structure (Fig. 3).

To further examine the strongest plasmonic mode, the electric-field intensity distribution in the x–z plane was extracted for the h/R = 3 configuration, as shown in Fig. 5. The results reveal that the electromagnetic energy remains strongly confined within the near-surface region of the nanocylinder and exhibits maximum localization near the upper edges of the metallic structure. The peak normalized field intensity reaches approximately 1.15, indicating a substantial enhancement relative to the surrounding region. This highly confined field distribution confirms that the h/R = 3 geometry supports the strongest plasmonic localization among the investigated configurations and therefore corresponds to the highest absorption response observed in Fig. 2.

The combined x–y and x–z field distributions provide direct evidence that aspect-ratio engineering controls both the magnitude and spatial confinement of the localized electromagnetic field. As the aspect ratio increases, stronger plasmonic hot spots are formed near the nanocylinder boundaries, leading to enhanced optical energy localization. Since photothermal generation is proportional to the local electric-field intensity, these highly localized electromagnetic regions are expected to act as nanoscale heat sources. Consequently, the near-field localization observed in Figs. 4 and 5 provides the physical basis for understanding the thermal distributions presented in the following section.

4.3 Plasmon-Induced Thermal Localization and Graphene-Mediated Heat Redistribution

The pronounced electromagnetic energy localization observed in Figs. 4 and 5 is expected to generate highly localized heat sources through non-radiative plasmon decay. Since the volumetric heat generation rate is directly proportional to the local electric-field intensity, regions exhibiting strong plasmonic hot spots also correspond to regions of enhanced photothermal generation. To investigate the thermal consequences of the observed near-field localization, the spatial temperature distribution of the nanocylinder array was analyzed under optical excitation. The resulting temperature distributions for graphene-free and graphene-coupled configurations are presented in Figs. 6 and 7, respectively.

Figure 6 presents the thermal response of the graphene-free structure. The thermal maps reveal that the regions of maximum temperature coincide with the locations of strongest plasmonic field localization. The maximum temperature reaches approximately 369 K, while the minimum temperature remains near 353 K, resulting in a temperature variation of approximately 16 K across the structure. The generated thermal energy remains highly confined around the plasmonic nanocylinders, producing pronounced thermal gradients and localized temperature accumulation. These observations indicate that in the absence of graphene, plasmon-induced heat remains concentrated near the optical hot spots, leading to strong thermal localization.

Figure 7 shows the thermal response of the graphene-coupled hybrid structure. Although the maximum temperature still occurs near the plasmonic hot spots, the overall temperature distribution becomes considerably more uniform. The maximum temperature is approximately 358 K, whereas the minimum temperature remains close to 356.8 K, yielding a temperature variation of only about 1.2 K. Compared with the graphene-free structure, the thermal gradients are substantially reduced and the generated heat spreads laterally throughout the structure. This behavior demonstrates that graphene actively participates in redistributing plasmon-induced thermal energy rather than acting solely as a passive optical interface.

The observed thermal redistribution behavior is consistent with previous reports describing graphene as an efficient heat-spreading material in hybrid optoelectronic and plasmonic systems [11, 26, 27].

The comparison between Figs. 6 and 7 clearly demonstrates the important thermal role of graphene in the hybrid nanostructure. The incorporation of graphene reduces the temperature variation from approximately 16 K to about 1.2 K, corresponding to a reduction of nearly 92.5% in thermal non-uniformity. Owing to its exceptionally high in-plane thermal conductivity, graphene provides an efficient pathway for redistributing plasmon-induced thermal energy throughout the structure. As a result, localized overheating is suppressed and the thermal stability of the hybrid plasmonic platform is significantly improved.

The results presented in the previous sections reveal a coupled but non-identical relationship between optical and thermal localization. Increasing the nanocylinder aspect ratio enhances plasmonic energy localization and strengthens near-field confinement, whereas the incorporation of graphene suppresses excessive thermal localization through efficient lateral heat redistribution. Consequently, strong optical confinement can be achieved without a proportional increase in localized thermal accumulation. This dual behavior enables simultaneous optical enhancement and thermal stabilization and forms the foundation of the proposed optical–thermal design framework.

Therefore, the combined optical and thermal analyses demonstrate that aspect-ratio engineering and graphene-assisted thermal redistribution together provide a coupled mechanism for controlling plasmonic energy localization in hybrid gold–graphene nanostructures. While the nanocylinder geometry governs plasmon resonance tuning and electromagnetic confinement, graphene regulates the spatial redistribution of plasmon-induced heat, thereby enhancing the thermal stability of the hybrid plasmonic platform.

4.4 Positioning of the Present Work within Hybrid Plasmonic Nanostructures

To position the present study within the context of previously reported plasmonic and graphene–plasmonic nanostructures, a comparison with representative studies from the literature is summarized in Table 1.

Table 1
Comparison of representative plasmonic and graphene–plasmonic nanostructures reported in the literature.

Thermal Analysis	Near-Field Enhancement	Plasmon Tunability	Main Objective	Structure	Reference
No	Moderate	Limited	Size-dependent plasmon resonance	Gold nanoparticles	[5]
No	Yes	Moderate	Photovoltage enhancement	Graphene–plasmonic hybrid structures	[14]
No	Strong	Moderate	Absorption enhancement	Graphene–antenna hybrid photodetector	[29]
No	Strong	Limited	Narrowband photodetection	Plasmonic photodetector nanostructures	[30]
Limited	Strong	Tunable	Optical absorption enhancement	Plasmonic nanostructures for photodetectors	[17]
Yes (graphene-assisted heat dissipation)	**Strong**	**Strong (aspect-ratio engineering)**	**Geometry-controlled plasmon resonance and photothermal localization**	**Gold nanocylinder–graphene hybrid array**	**This Work**

As summarized in Table 1, most previously reported plasmonic nanostructures primarily focused on optical absorption enhancement, resonance tunability, or photodetection performance. Although several graphene–plasmonic hybrid systems demonstrated enhanced electromagnetic localization and improved optical response, the thermal behavior of plasmon-induced localized energy has received comparatively limited attention.

In contrast to earlier studies, the present work demonstrates that aspect-ratio engineering of gold nanocylinder arrays provides simultaneous control over plasmon resonance tuning, near-field electromagnetic localization, and photothermal energy distribution within a unified hybrid platform. The comparative analysis between graphene-coupled and graphene-free configurations further reveals that graphene actively regulates the spatial redistribution of plasmon-induced thermal energy owing to its exceptionally high in-plane thermal conductivity.

Unlike conventional plasmonic studies that primarily emphasize optical absorption enhancement, the present work establishes a direct physical relationship between geometry-dependent plasmon resonance, electromagnetic energy localization, localized heat generation, and graphene-mediated thermal redistribution. These results highlight the importance of combining geometric plasmonic engineering with thermally conductive two-dimensional materials for the development of thermally stable hybrid nanophotonic structures.

The present results further support recent reports indicating that geometric parameters play a decisive role in determining the spatial localization of plasmonic energy within hybrid nanostructures. In particular, aspect-ratio engineering has emerged as an effective strategy for controlling resonance characteristics and electromagnetic confinement in plasmonic nanostructures [5–8].

4.5 Optical–Thermal Stability Analysis

The results presented in the previous sections reveal a coupled but non-identical relationship between optical and thermal localization. While increasing the nanocylinder aspect ratio enhances plasmonic energy localization, strengthens near-field confinement, and increases optical absorption, the incorporation of graphene suppresses excessive thermal localization through efficient lateral heat redistribution. Consequently, strong optical confinement can be achieved without a proportional increase in localized thermal accumulation.

For the purpose of quantitative comparison within the present study, two performance indicators are defined to evaluate the balance between optical enhancement and thermal stabilization. The first parameter, referred to as the Optical–Thermal Stability Factor (OTSF), is defined as

$$\varvec{OTSF} = \frac{\varvec{A}_{\varvec{peak}}}{\Delta \varvec{T}}$$

where A_{peak} is the maximum optical absorption and ΔT represents the temperature variation across the structure, defined as the difference between the maximum and minimum temperatures. A larger OTSF value indicates a more favorable combination of strong optical absorption and reduced thermal non-uniformity.

The second parameter, termed the Thermal Uniformity Improvement (TUI), is introduced to quantify the effectiveness of graphene in reducing thermal localization:

$$\varvec{TUI} = \frac{\Delta \varvec{T}_{\varvec{without}} - \Delta \varvec{T}_{\varvec{with}}}{\Delta \varvec{T}_{\varvec{without}}} \times 100$$

where $\Delta T_{without}$ and ΔT_{with} denote the temperature variations of the graphene-free and graphene-coupled structures, respectively. This parameter directly measures the degree of thermal stabilization achieved through graphene-assisted heat spreading.

Based on the absorption and thermal results obtained in the present study, the corresponding performance metrics are summarized in Table 2.

Table 2
Quantitative optical–thermal performance comparison of graphene-free and graphene-coupled nanostructures.

Parameter	Without Graphene	With Graphene
Peak Absorption (a.u.)	5.8	6.6
T_{max} (K)	369	358
T_{min} (K)	353	356.8
ΔT (K)	16	1.2
OTSF ($a.u.K^{-1}$)	0.36	5.50
TUI (%)	—	92.5

As shown in Table 2, the incorporation of graphene dramatically improves the optical–thermal performance of the hybrid nanostructure. Although the optical absorption remains high and even slightly increases in the graphene-coupled configuration, the temperature variation decreases from approximately 16 K to only about 1.2 K. As a result, the OTSF increases from approximately 0.36 to 5.50, corresponding to an enhancement of more than one order of magnitude.

The calculated TUI value of approximately 92.5% further confirms the effectiveness of graphene as a thermal redistribution layer. Owing to its exceptionally high in-plane thermal conductivity, graphene efficiently spreads the plasmon-generated heat throughout the structure, suppressing localized thermal accumulation while preserving strong plasmonic energy localization.

These findings demonstrate that optical enhancement and thermal stabilization are not necessarily competing objectives in hybrid plasmonic systems. Instead, geometry-controlled plasmonic localization and graphene-assisted thermal redistribution perform complementary functions. The nanocylinder aspect ratio governs resonance tuning and electromagnetic confinement, whereas graphene regulates heat transport and thermal uniformity. This dual mechanism establishes an integrated optical–thermal design framework for the development of thermally stable hybrid plasmonic nanostructures.

5. Conclusion

The principal outcome of this study is the demonstration that aspect-ratio engineering and graphene-assisted heat spreading perform complementary functions in hybrid plasmonic nanostructures. While nanocylinder geometry enhances plasmonic energy localization, graphene mitigates excessive thermal localization, thereby enabling thermally stable plasmonic enhancement.

In this work, a hybrid gold–graphene nanophotonic platform consisting of ordered arrays of gold nanocylinders supported on a graphene-coated SiO_2 substrate was systematically investigated through coupled electromagnetic and thermal simulations. The study examined the influence of nanocylinder aspect ratio on plasmon resonance behavior, near-field electromagnetic confinement, and photothermal energy redistribution.

The results demonstrate that increasing the height-to-radius ratio significantly enhances plasmonic energy localization, resulting in stronger near-field confinement and increased optical absorption. The formation of highly localized plasmonic hot spots confirms the dominant role of geometric design in controlling electromagnetic energy concentration within the hybrid structure.

The thermal analysis further reveals that plasmon-induced heat generation remains spatially correlated with the regions of strongest electromagnetic localization. However, the presence of graphene substantially modifies the resulting temperature distribution. Owing to its exceptionally high in-plane

thermal conductivity, graphene provides an efficient lateral pathway for heat transport, enabling rapid redistribution of plasmon-generated thermal energy. Consequently, heat generation remains localized near the plasmonic hot spots, whereas the temperature field becomes significantly more uniform.

Quantitative comparison between graphene-free and graphene-coupled configurations shows that the temperature variation across the structure decreases from approximately 16 K to about 1.2 K, corresponding to a thermal uniformity improvement of nearly 92.5%. At the same time, strong optical absorption is preserved, resulting in an increase of the proposed Optical–Thermal Stability Factor (OTSF) by more than one order of magnitude. These findings demonstrate that optical enhancement and thermal stabilization are not necessarily competing objectives in hybrid plasmonic systems.

The principal scientific contribution of this work lies in establishing an integrated optical–thermal framework linking aspect-ratio-controlled plasmon resonance tuning, near-field electromagnetic localization, localized heat generation, and graphene-mediated thermal redistribution. The results show that aspect-ratio engineering governs plasmonic localization, whereas graphene-assisted thermal diffusion regulates temperature localization. Together, these mechanisms provide a unified strategy for simultaneously achieving strong optical confinement and thermal stability.

Overall, the proposed gold nanocylinder–graphene architecture offers a promising platform for the development of thermally robust plasmonic devices and advanced nanophotonic systems. The design principles identified in this study may be applicable to plasmon-enhanced sensors, photodetectors, energy-conversion devices, and other hybrid optoelectronic technologies where efficient optical confinement and thermal management must be achieved simultaneously. Future work may focus on experimental validation of the proposed structure, optimization of interparticle coupling effects, and exploration of alternative two-dimensional materials for enhanced optical–thermal functionality.

Declarations

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with Ethical Standards

Conflict of Interest

No potential conflict of interest was reported by the authors.

Consent to Participate

The authors of this paper voluntarily agree to participate in this research study.

Author contributions

Mohammad Sadegh Akhoundi Khezrabad: Supervision, Writing - Review & Editing, Investigation, Formal analysis, Validation, Conceptualization

Samira Zolfaghari Nikanjam: Writing, Investigation, Formal analysis, Validation, Software

This manuscript has not been submitted to, nor is it under review at, another journal or other publishing venue.

Research funding

This research did not receive funding

References

1. Maier SA (2007) Plasmonics: Fundamentals and applications. Springer
2. Stockman MI (2011) Nanoplasmonics: The physics behind the applications. Phys Today 64(2):39–44. https://doi.org/10.1063/1.3554315
3. Atwater HA, Polman A (2010) Plasmonics for improved photovoltaic devices. Nat Mater 9(3):205–213. https://doi.org/10.1038/nmat2629
4. Brongersma ML, Halas NJ, Nordlander P (2015) Plasmon-induced hot carrier science and technology. Nat Nanotechnol 10(1):25–34. https://doi.org/10.1038/nnano.2014.311
5. Link S, El-Sayed MA (1999) Size and temperature dependence of the plasmon absorption of colloidal gold nanoparticles. J Phys Chem B 103(21):4212–4217
6. Link S, El-Sayed MA (2000) Shape and size dependence of radiative, non-radiative and photothermal properties of gold nanocrystals. Int Rev Phys Chem 19(3):409–453
7. Jain PK, Lee KS, El-Sayed IH, El-Sayed MA (2006) Calculated absorption and scattering properties of gold nanoparticles of different size, shape, and composition. J Phys Chem B 110(14):7238–7248
8. Kelly KL, Coronado E, Zhao LL, Schatz GC (2003) The optical properties of metal nanoparticles: The influence of size, shape, and dielectric environment. J Phys Chem B 107(3):668–677
9. Castro Neto AH, Guinea F, Peres NMR, Novoselov KS, Geim AK (2009) The electronic properties of graphene. Rev Mod Phys 81(1):109–162. https://doi.org/10.1103/RevModPhys.81.109

10. Novoselov KS, Fal'ko VI, Colombo L, Gellert PR, Schwab MG, Kim K (2012) A roadmap for graphene. Nature 490(7419):192–200. https://doi.org/10.1038/nature11458
11. Sang M, Shin J, Kim K, Yu KJ (2019) Electronic and thermal properties of graphene and recent advances in graphene based electronics applications. Nanomaterials 9(3):374. https://doi.org/10.3390/nano9030374
12. Nair RR, Blake P, Grigorenko AN, Novoselov KS, Booth TJ, Stauber T, Peres NMR, Geim AK (2008) Fine structure constant defines visual transparency of graphene. Science 320(5881):1308. https://doi.org/10.1126/science.1156965
13. Koppens FHL, Mueller T, Avouris P, Ferrari AC, Vitiello MS, Polini M (2014) Photodetectors based on graphene, other two-dimensional materials and hybrid systems. Nat Nanotechnol 9(10):780–793. https://doi.org/10.1038/nnano.2014.215
14. Echtermeyer TJ, Britnell L, Jasnos PK, Lombardo A, Gorbachev RV, Grigorenko AN, Geim AK, Ferrari AC, Novoselov KS (2011) Strong plasmonic enhancement of photovoltage in graphene. Nat Commun 2:458
15. Fang Z, Liu Z, Wang Y, Ajayan PM, Nordlander P, Halas NJ (2014) Active tunable absorption enhancement with graphene nanodisk arrays. Nano Lett 14(1):299–304. https://doi.org/10.1021/nl403803h
16. Tielrooij KJ, Massicotte M, Piatkowski L, Woessner A, Ma Q, Jarillo-Herrero P, van Hulst NF, Koppens FHL (2015) Hot-carrier photocurrent effects at graphene–metal interfaces. Nat Nanotechnol 10(5):437–443. https://doi.org/10.1038/nnano.2015.54
17. Zhang Y, Li Y, Xu H (2020) Plasmonic nanostructures for enhanced light absorption in photodetectors. Nanophotonics 9(6):1315–1332. https://doi.org/10.1515/nanoph-2019-0406
18. Wang Y, Li Z, Xu H (2023) Hybrid graphene–plasmonic nanostructures for enhanced light–matter interaction. Nanophotonics 12(7):1123–1141
19. Zhang Z, Lee Y, Haque MF et al (2022) Plasmonic sensors based on graphene and graphene hybrid materials. Nano Convergence 9:28. https://doi.org/10.1186/s40580-022-00319-5
20. Herkert EK, Bermeo Alvaro DR, Recchia M, Langbein W, P.Borri, and, Garcia-Parajo MF (2023) Hybrid plasmonic nanostructuresfor enhanced single-molecule detection sensitivity. ACS Nano, 17, 9, pp. 8453 – 8464
21. Khurgin J, Bykov AY, Zayats AV (2024) Hot-electron dynamics in plasmonic nanostructures: fundamentals, applications and overlooked aspects. eLight 4:15. https://doi.org/10.1186/s43593-024-00070-w
22. Jelver L, Cox JD (2024) Nonlinear Thermoplasmonics in Graphene Nanostructures. NanoLett. 24, 13775– 13782. https://doi:10.1021/acs.nanolett.4c04048
23. Babicheva VE (2023) Optical Processes behind Plasmonic Applications. Nanomaterials 13(7):1270. https://doi.org/10.3390/nano13071270
24. Baffou G, Quidant R (2013) Thermo-plasmonics: Using metallic nanostructures as nano-sources of heat. Laser Photonics Rev 7(2):171–187
25. Baffou G, Kreuzer MP, Kulzer F, Quidant R (2009) Temperature mapping near plasmonic nanostructures. Phys Rev Lett 103:267801
26. Balandin AA (2011) Thermal properties of graphene and nanostructured carbon materials. Nat Mater 10(8):569–581
27. Ghosh S, Bao W, Nika DL et al (2010) Dimensional crossover of thermal transport in few-layer graphene. Nat Mater 9(7):555–558
28. Johnson PB, Christy RW (1972) Optical constants of the noble metals. Phys Rev B 6(12):4370–4379. https://doi.org/10.1103/PhysRevB.6.4370
29. Fang Z, Liu Z, Wang Y, Ajayan PM, Nordlander P, Halas NJ (2012) Graphene–antenna sandwich photodetector. Nano Lett 12(7):3808–3813
30. Sobhani A, Knight MW, Wang Y, Zheng B, King NS, Brown LV, Fang Z, Nordlander P, Halas NJ (2013) Narrowband photodetection in the near-infrared with a plasmon-induced hot electron device. Nat Commun 4:1643. https://doi.org/10.1038/ncomms2648

Figures

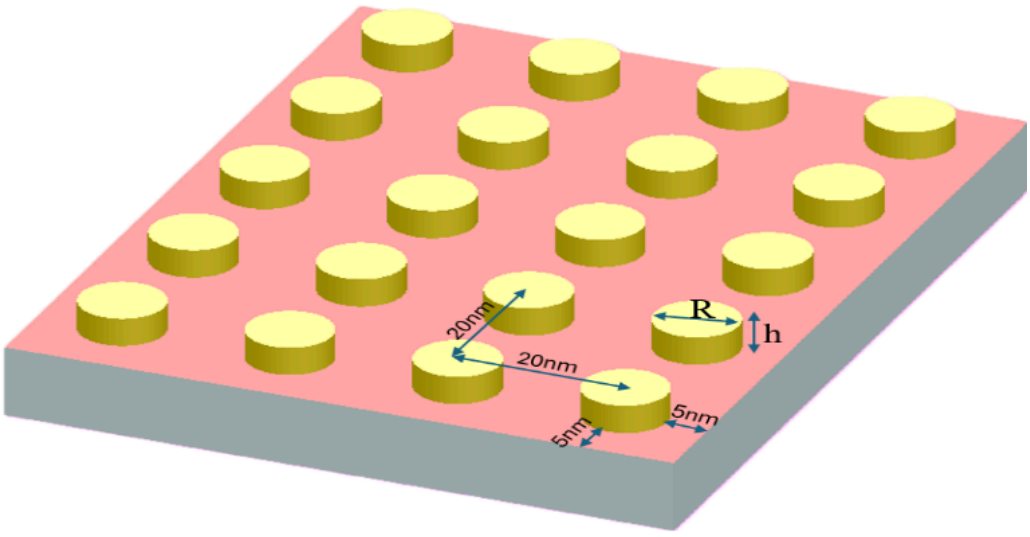


Figure 1

Schematic representation of the simulated hybrid nanophotonic structure consisting of an ordered array of gold nanocylinders placed on a graphene layer supported by a SiO_2 substrate.

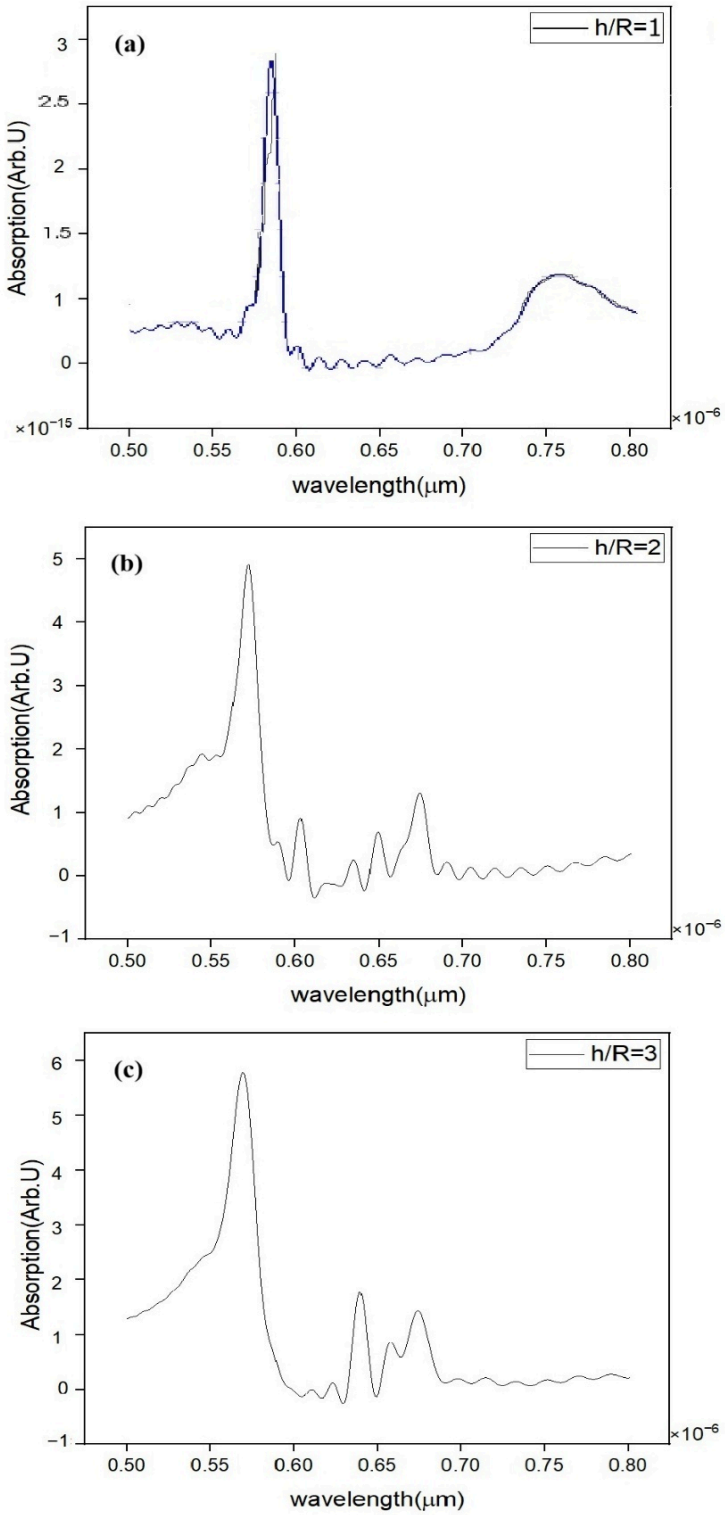


Figure 2

Optical absorption spectra of the proposed gold nanocylinder array without the graphene layer for three different aspect-ratio configurations: (a) h/R=1, (b) h/R=2, and (c) h/R=3.

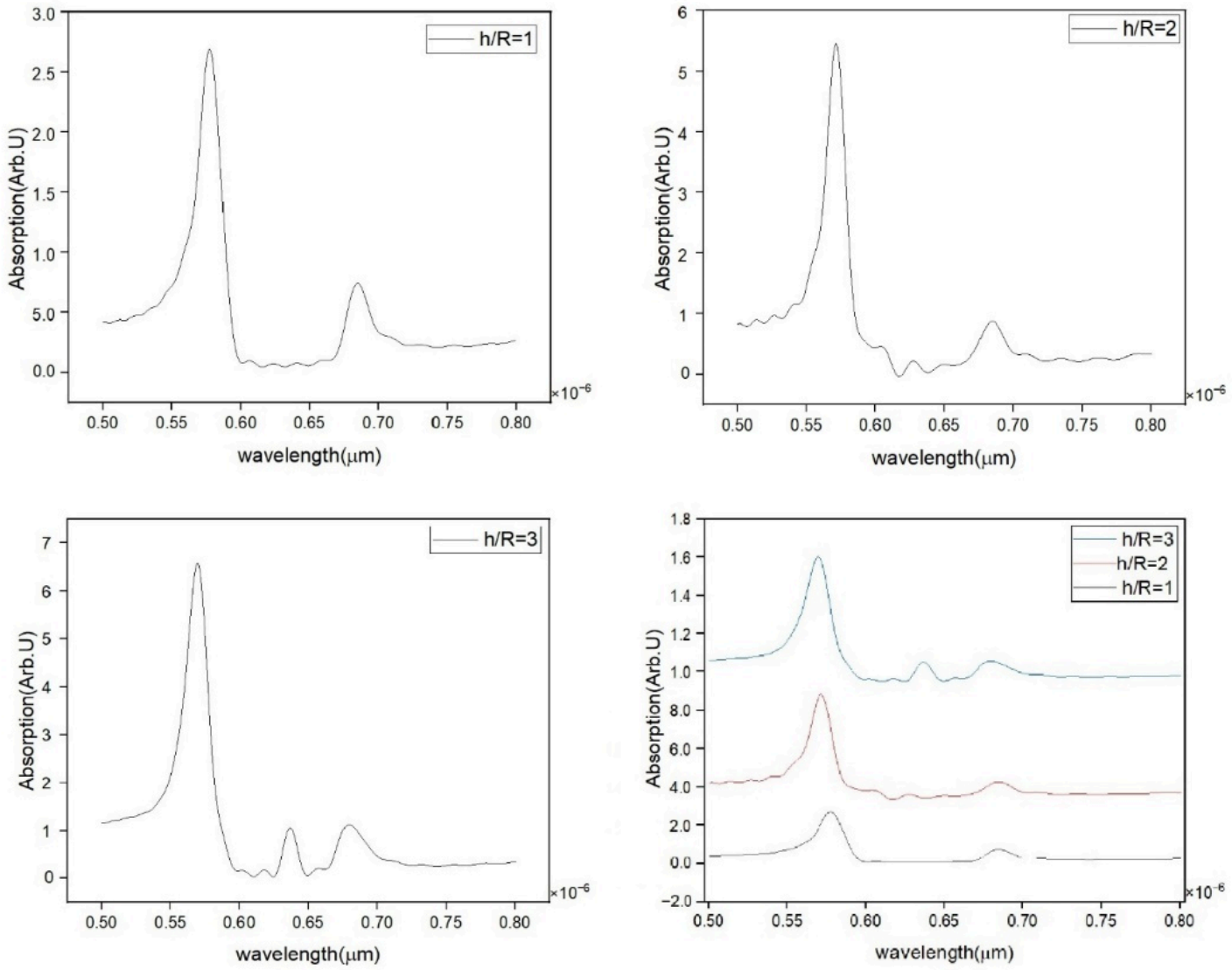


Figure 3

Optical absorption spectra of the hybrid gold–graphene nanostructure for different nanocylinder aspect ratios (h/R = 1, 2, and 3).

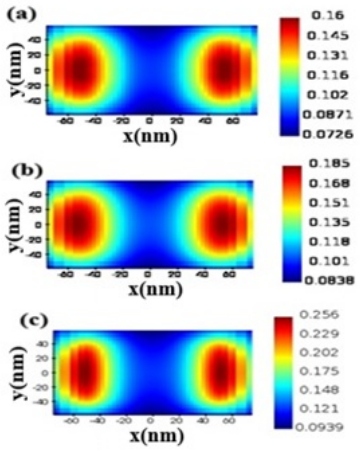


Figure 4

Spatial distribution of the normalized electric-field intensity in the x–y plane of the hybrid gold–graphene nanocylinder array for different aspect ratios: (a) h/R=1, (b) h/R=2, and (c) h/R=3.

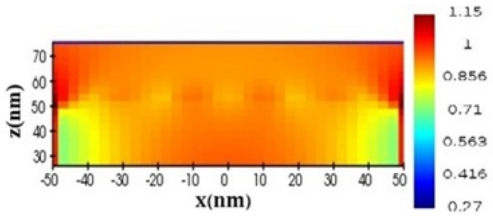


Figure 5

Spatial distribution of the normalized electric-field intensity in the x–z plane of the hybrid gold–graphene nanocylinder array for h/R=3.

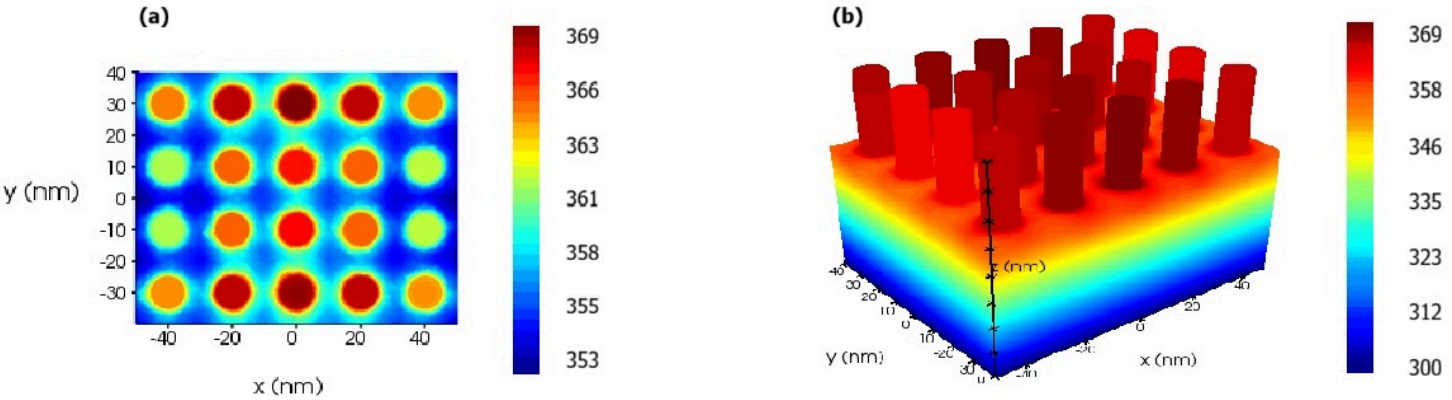


Figure 6

Two-dimensional and three-dimensional temperature distributions of the proposed gold nanocylinder array in the absence of graphene.

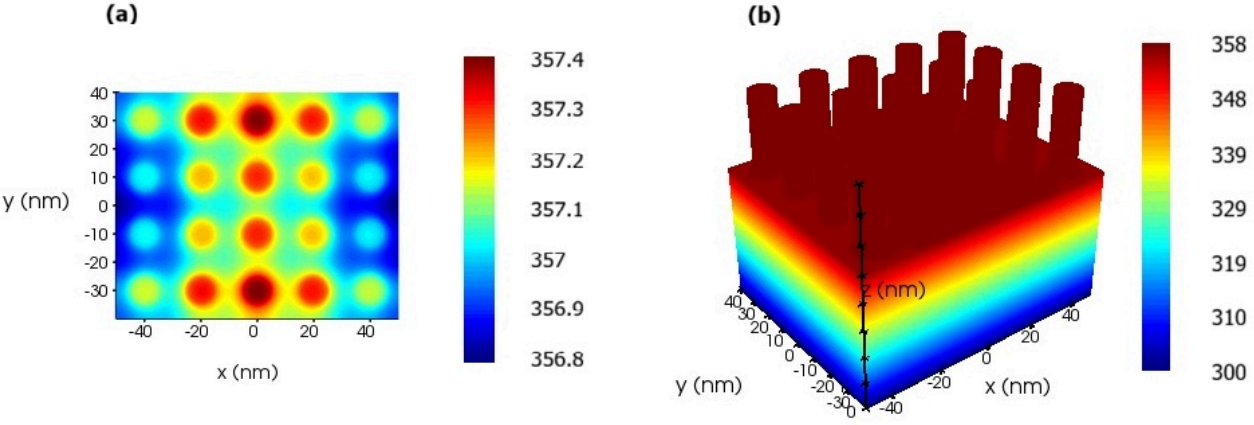


Figure 7

Two-dimensional and three-dimensional temperature distributions of the proposed hybrid gold–graphene nanocylinder array under optical excitation.