

Modified light emission from a dipole in lossy and graded-index spherical structures

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Energy transfer and light emission behavior at subwavelength scales are governed by near-field interactions between an emitter and its surrounding refractive-index environment, which can modify emission at the nanoscale and influence the far-field response in devices such as solar cells and light-emitting diodes (LEDs). Here, we analyze light emission in a spherical structure using a classical point dipole model with emphasis on how near-field interactions affect the spontaneous emission rate, as quantified by the Purcell factor. The system is studied under two refractive-index configurations: (1) an abrupt transition from an inner sphere to the surrounding medium and (2) a gradual transition with a graded refractive index, considered for both nonabsorbing and absorbing surrounding media. Our findings show that, within the fixed-amplitude dipole considered here, even a strong increase in near-field absorption does not lead to a comparable reduction in the far-field emission. In this model, the source supplies the additional power required to compensate for such near-field losses. This distinction between near-field enhancement and radiated power to the far field is important, for example, in studies of photon recycling in semiconductors and other optoelectronic devices, where both near-field absorption and radiative emission are present. An abrupt transition in the refractive index produces repeated peaks in the Purcell factor as a function of the inner sphere radius, whereas a graded refractive index smooths these peaks. In a graded system, with increasing grading thickness, the Purcell factor converges to the refractive index of the inner sphere when the grading thickness reaches the order of the wavelength. This behavior indicates that, even when the inner sphere has a higher refractive index than the surrounding medium, the emission is not limited by the surrounding refractive index. Thus, a graded refractive-index profile provides a viable strategy for mitigating reflection losses in emission. These insights are valuable for designing photon out-coupling and photon-recycling schemes and offer a pathway for improving the performance of optoelectronic devices, including solar cells and LEDs.

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I. INTRODUCTION

Controlling light-matter interactions at subwavelength scales has attracted significant attention because such control enables precise manipulation of optical energy in nanostructured systems. In such nanoscale environments, energy transfer rates can exceed the far-field limit of conventional blackbody radiation [1], highlighting the unique opportunities offered by near-field interactions. Understanding and harnessing these interactions is essential for a wide range of applications in nanophotonic and nanoscale energy management [2–8]. In optical systems, controlling light emission and extraction from emitters embedded in multilayer or nanoscale structures relies on similar light-matter interactions. For example, it has been shown that the spontaneous emission rate of an atom can be either suppressed or enhanced when placed inside an optical cavity [9]. Dielectric boundaries have also been demonstrated to significantly alter atomic emission rates, both for atoms positioned near spherical interfaces [10] and for those embedded inside dielectric spheres. Transient quantum electrodynamic effects in dispersive and absorbing media have been studied to understand how the spontaneous emission rate of an atom evolves toward a steady-state equilibrium [11]. Theoretical investigations of the spontaneous decay of excited atoms in absorbing cavities have revealed that the decay rate depends on the cavity radius, particularly for frequencies near the medium’s absorption band [12]. Indeed, theoretical studies have shown that the spontaneous emission rate of a single atom can be modified by a dielectric surrounding across the full frequency spectrum, including regions near the resonances of the medium [13]. Experimentally, it has been demonstrated that the radiative decay rate of a quantum emitter can depend not only on the local density of optical states (LDOS) associated with electric-dipole transitions (electric LDOS), but also on the combined electromagnetic LDOS, which includes both electric and magnetic contributions [14]. Studies of the transition rates of atoms placed inside a spherical dielectric particle have shown that the atomic position within the particle significantly affects the calculated emission and absorption rates [15]. Furthermore, understanding light emission is critical for analyzing and optimizing the performance of many optoelectronic devices. In solar cells, for example, efficient light emission is essential for optimizing radiative recombination and photon recycling. Photon recycling refers to the process in which emitted photons are reabsorbed and reemitted within the device [9, 16–19]. These processes are key to improving open-circuit voltage and overall efficiency, particularly in solar cells operating near the radiative, detailed-balance limit [20–25]. Similarly, in light-emitting diodes (LEDs), the photon emission rate, internal photon recycling, and parasitic absorption determine radiative efficiency, as well as key factors like color purity and brightness [26–28]. The performance of laser diodes also depends on light emission, as enhancing the stimulated emission relies on precise control of emission dynamics [29].

In this study, we investigate modified light emission in nanostructures by analyzing a spherically symmetric system with inhomogeneous refractive-index distributions. The emitter is modeled as a fixed-amplitude dipole source, representing a classical driven source with a specified dipole moment. This model is distinct from a microscopic two-level emitter in which parasitic absorption introduces an additional loss channel that can reduce the emitted power. It is therefore most relevant as an electromagnetic description of idealized driven emission or photon-recycling scenarios in continuous semiconductor media. Electromagnetic simulations account for both near-field and far-field optical effects. The refractive-index distribution is taken either as abrupt at layer boundaries or as a smooth radial graded variation $n(r)$. Such graded refractive-index structures have been widely used to improve the performance of solar cells and LEDs—in solar cells, smooth refractive-index transitions between different layers enhance light absorption [30], while in LEDs, graded-index antireflection layers improve light extraction by reducing internal reflections [31]. Such grading can be realized by stacking several layers with slightly different refractive indices, continuously varying material composition, or by using nanostructured surfaces [32].

Building on foundational theoretical treatments of dipole emission in complex dielectric environments [33], including Mie theory [34], dyadic Green’s function formulations for layered spherical media [35], emission near dielectric interfaces [36], and dipole emitters embedded in or adjacent

to spherical dielectric structures [37], the present work focuses on a question that has not been fully resolved in the form considered here: the relationship between local near-field dissipation and far-field radiated power in absorbing environments within a fixed-amplitude dipole model. We address this point by explicitly distinguishing these contributions using a full-wave electromagnetic approach.

In numerical modeling, such strong near-field effects usually require proper regularization to avoid unphysical divergences. Macroscopic quantum electrodynamics approaches address this issue by subtracting the dipole self-interaction through Green's-tensor decompositions or formulations compatible with detailed balance [38,39]. Other numerical strategies have included finite-size dipole models, spatial averaging procedures, and local-field corrections, which effectively moderate near-field singular behavior in practical simulations [40,41]. Our modeling extends previous approaches by (1) controlling light out-coupling from embedded spherical domains, such as quantum dots or atomic sources; (2) distinguishing near-field and far-field effects on light-matter interactions and energy transfer mechanisms; (3) indicating that even a strong increase in near-field absorption does not noticeably affect the far-field emission from a dipole; (4) analyzing the impact of abrupt versus smooth refractive-index transitions on emission; and (5) providing insight into internal emission processes, as relevant for photovoltaics and LEDs.

This work is organized as follows. The proposed geometry and the details of the numerical methods used to simulate emission are described in Sec. II. Section III presents results for both abrupt and graded refractive-index distribution in nonabsorbing and absorbing media, including the effects of off-center emitter placement and the distinction between continuous semiconductor regions and discrete two-level systems. Finally, Sec. IV contains the conclusions.

II. GEOMETRY AND METHODS

We investigate light emitted from a spherical structure of refractive index n_1 and radius r_{inner} , surrounded by a medium of refractive index n_2 . A dipole, located at the center of the structure, acts as an emitter. This centered-emitter configuration is chosen to isolate the effect of the refractive-index profile in the highest-symmetry case, for which the total emitted power is independent of dipole orientation. To assess the robustness of the results beyond the centered-emitter configuration, we also consider, at the end of this paper, representative off-center dipole positions for both the abrupt and graded-index transitions. We choose an example wavelength of $\lambda = 1070$ nm for the study. Figure 1 shows the structure under study. We analyze two specific cases: (1) $n_1 = 1.5$ and $n_2 = 3.3$ and (2) the inverse case of $n_1 = 3.3$ and $n_2 = 1.5$. These refractive indices are chosen to represent typical glass ($n_1 = 1.5$) and a higher refractive-index semiconductor ($n_2 = 3.3$). We consider for each of these two cases two scenarios: (1) nonabsorbing surrounding medium, that is, when $\text{Im}(n_2) = 0$, and (2) absorbing surrounding medium with $\text{Im}(n_2) = 0.01$ that corresponds to a bulk absorption length of $(4\pi\text{Im}(n_2)/\lambda)^{-1} = 8.5$ μm . The analysis is conducted using the finite element method (FEM) via the Wave Optics Module in COMSOL Multiphysics, solving with linear, local, isotropic, nonmagnetic, and time-harmonic Maxwell's equations for the diffraction of light [42]. To continue the outer domain to infinity in our modeling, we include a perfectly matched layer (PML) domain, starting at a radius r_{outer} . We verified that r_{outer} was chosen sufficiently large in our modeling so that its exact value did not influence the emitted power. The dipole is included in the model as a point dipole that has a fixed dipole orientation with strength p_{dip} . This corresponds to a harmonically driven source whose dipole moment is maintained independently of the local electromagnetic environment, allowing the total power supplied by the source to vary in response to changes in the surrounding medium [41]—this modified emission rate is described by the Purcell effect [43].

To obtain numerical convergence of the emission from the dipole, a small auxiliary spherical domain with refined meshing was introduced surrounding the dipole (the radius of this sphere ranged from 1 to 5 nm, increasing with r_{inner}). Inside this auxiliary region, which has the same n_1 as the

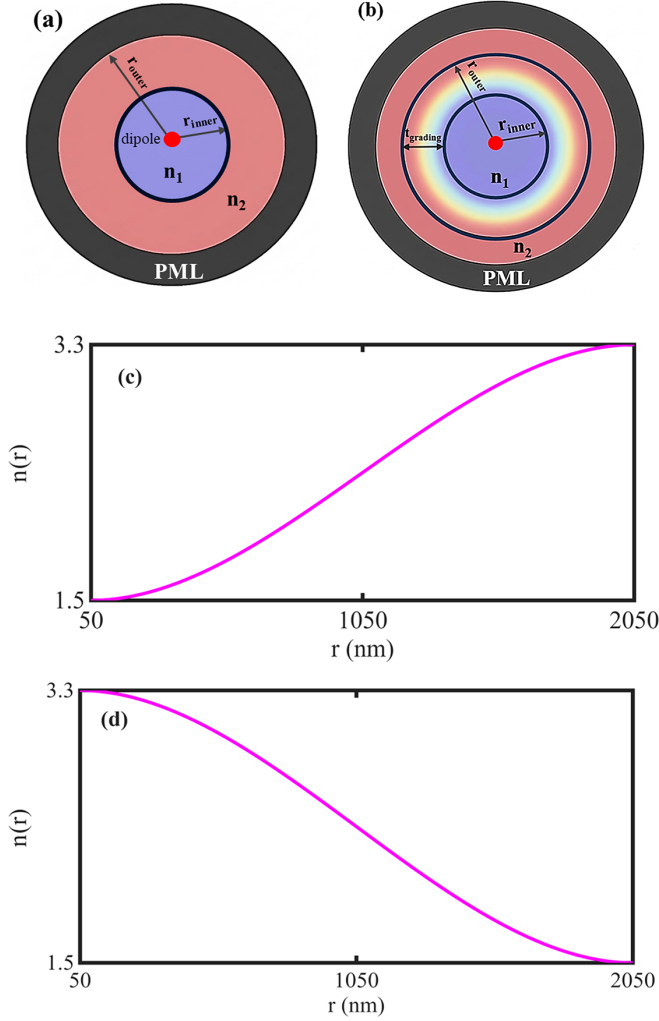


FIG. 1. (a), (b) Two-dimensional schematic of the dipole emitter-based modeling with dipole (red circle in the center), inner sphere of radius r_{inner} and outer simulation sphere of r_{outer} , beyond which the PML is placed to extend the outer sphere in practice to infinity. In this schematic, the refractive index exhibits (a) an abrupt change at $r = r_{\text{inner}}$ and (b) a gradual transition between the inner and outer spheres over a thickness t_{grading} . (c), (d) The corresponding spatial profiles of the graded refractive index for $r_{\text{inner}} = 50$ nm, $t_{\text{grading}} = 2000$ nm, varying smoothly from (c) 1.5 to 3.3 and (d) 3.3 down to 1.5 (see Sec. II for details).

inner sphere, finite-element size was on the order of 0.5 nm, while coarser mesh elements were used in the surrounding n_1 medium to reduce computational cost.

We note that this auxiliary domain is used purely for numerical purposes to allow finer meshing in the FEM to handle the singular behavior of the point dipole—we note that additionally, physical emitters such as atoms, molecules, or quantum dots have a finite size and do not produce a true singular field at $r \rightarrow 0$ [44]. The FEM results were verified for convergence by testing multiple auxiliary sphere radii spanning the practical numerical regime used in the simulation, confirming that the results are robust and do not depend on the arbitrary size of this auxiliary spherical domain. For the case of the abrupt transition in the refractive index from n_1 to n_2 at $r = r_{\text{inner}}$, r_{outer} is set to be twice the size of r_{inner} for $r_{\text{inner}} > 200$ nm, and for smaller r_{inner} ,

we use $r_{\text{outer}} = \lambda/4$. For the case of the smooth radial variation of the refractive index, the grading starts at $r_{\text{inner}} = 50$ nm and extends over a region of thickness t_{grading} that is varied from 1 to 2000 nm. In this case, the outer radius is defined as $r_{\text{outer}} = r_{\text{inner}} + t_{\text{grading}} + 300$ nm. The (possibly complex-valued) refractive index in the graded region is modeled using a function with zero derivative set at both the beginning and end of the transition region, varying smoothly from n_1 to n_2 (this is accomplished by performing cubic spline interpolation on the position and value vectors $[r_{\text{inner}}, r_{\text{inner}} + \delta, r_{\text{inner}} + t_{\text{grading}}/2, r_{\text{inner}} + t_{\text{grading}} - \delta, r_{\text{inner}} + t_{\text{grading}}]$ and $[n_1, n_1, (n_1 + n_2)/2, n_2, n_2]$ where $\delta = 0.01$ nm). In the absorbing case, both the real and imaginary parts of the refractive index are interpolated with the same spline and the same δ . The resulting smooth radial variation is illustrated in Figs. 1(c) and 1(d). Note that the largest r_{inner} in the abrupt case, 2050 nm, corresponds to $r_{\text{inner}} + t_{\text{grading}} = 2050$ nm (for the largest t_{grading} considered) in the smooth case, ensuring a fair comparison between abrupt and smooth transitions.

Our focus is on the emitted power (P_{em}) from the dipole with dipole moment p_{dip} . For reference, we use $P_{\text{ref}} = \frac{\omega^2 p_{\text{dip}}^2}{12\epsilon_0 c^3}$, which is the emitted power of the dipole when placed in vacuum [45]. We present the results in terms of normalized power, i.e., $P_{\text{em}}/P_{\text{ref}}$. To represent an isotropic dipole, we should average the results for x -, y -, and z -oriented dipole moments [43]. Although a single dipole emits anisotropically, the total emitted power P_{em} , obtained by integrating the radiated power over all angles, is independent of the dipole orientation when the emitter is placed exactly at the center of a spherically symmetric, isotropic structure. Therefore, instead of averaging over x -, y -, and z -oriented dipoles, we simulate a single dipole orientation to reduce computational cost.

In the simulations, to calculate P_{em} , we integrate the Poynting vector (projected onto the outward-directed normal vector of the surface) over a closed spherical surface. When we choose r_{inner} for the radius of that spherical surface, and the volume enclosed by the surface does not contain absorbing material, $P_{\text{em}}/P_{\text{ref}}$ yields the Purcell factor. However, if absorbing material is present near the dipole [$\text{Im}(n) > 0$], near-field absorption introduces an additional dissipation channel. In our fixed-amplitude dipole model, the source maintains its dipole moment, so that the total power supplied by the dipole increases in the presence of these additional dissipation channels; this increase is directly reflected in the value of $P_{\text{em}}/P_{\text{ref}}$ calculated at r_{inner} . For example, in a semiconductor system with photon recycling, this corresponds to assuming ideal photon recycling, where all the emitted energy that is absorbed in the near field is eventually returned to the emitter.

If, in the case of [$\text{Im}(n) > 0$], we choose a radius larger than r_{inner} for extracting P_{em} , the calculation includes the effects of absorption in the volume enclosed by the surface; strictly speaking, P_{em} then represents the net power reaching that specific distance after accounting for near-field absorption, rather than the total power dissipated by the source. Therefore, in the lossy case, $P_{\text{em}}/P_{\text{ref}}$ evaluated at radii larger than r_{inner} is not interpreted here as the Purcell factor, but rather as the net outward power after propagation through the absorbing region.

The spherical symmetry of the system, including the position of the dipole at $r = 0$, enables us to apply mirror symmetry along the x - z , x - y , and y - z planes [46]. This symmetry reduction reduces the computational domain, thereby speeding up calculations and reducing the necessary random-access memory. By leveraging these mirror symmetries, we model only 1/8 of the spherical system, confined to the positive half-spaces. For the symmetry reduction, we apply perfect electric-conductor boundary conditions to a plane perpendicular to the dipole moment and perfect magnetic-conductor boundary conditions to a plane parallel to the dipole moment. For the case of nonabsorbing materials, the STRATIFY MATLAB code [47] was used to validate the numerical results, showing good agreement and confirming the reliability of our COMSOL Multiphysics simulations. With the meshing settings that we used in COMSOL Multiphysics, we reached a relative convergence on the order of 2% relative to highly converged results from STRATIFY. We chose COMSOL Multiphysics for our studies due to its flexibility, including the case of an absorbing surrounding medium.

Although the results are presented for a specific wavelength to give direct comparison with practical device dimensions, it is understood that the results remain valid if the wavelength and

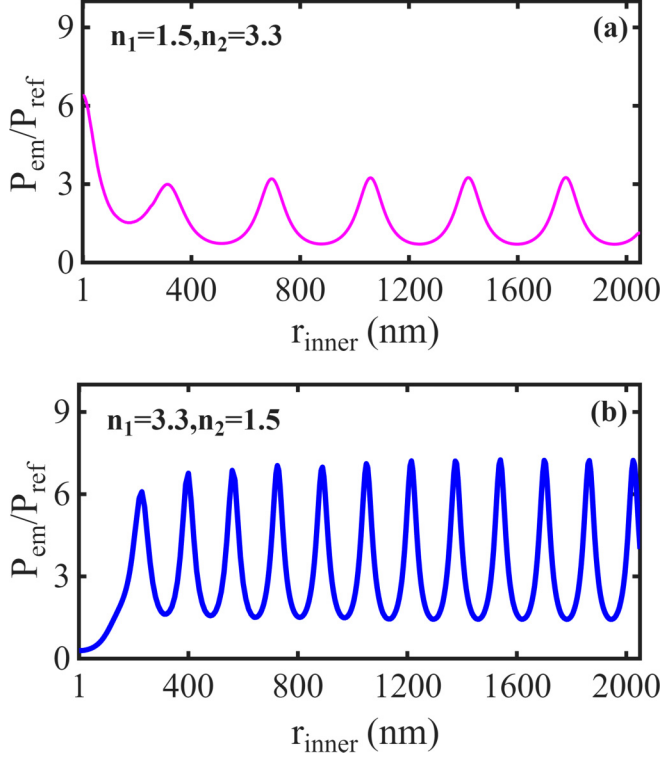


FIG. 2. $P_{\text{em}}/P_{\text{ref}}$ for a sharp transition in refractive index at r_{inner} with (a) $n_1 = 1.5, n_2 = 3.3$; and (b) $n_1 = 3.3, n_2 = 1.5$. Here, P_{em} is calculated from a spherical surface at r_{inner} , but the choice for this radius does not affect these results, since the system does not include absorbing material (within the domains enclosed by the PML).

geometrical dimensions are scaled in the same manner (as long as the refractive index does not show variation during this wavelength shift).

III. RESULTS

A. Abrupt transition in refractive index

We start by considering $\text{Im}(n) = 0$ for the outer sphere to focus on the underlying diffractive tuning of the emission properties, before additional effects from absorption are included [48]. As shown in Fig. 2, the sharp interface between n_1 and n_2 leads to reflection and refraction effects, resulting in peaks and dips in $P_{\text{em}}/P_{\text{ref}}$.

At small radii ($r \ll \lambda$), such that $(2\pi n_1/\lambda)r_{\text{inner}} \ll 1$, the system operates in the electrostatic regime and retardation effects are negligible, meaning that the phase of the electromagnetic field does not vary significantly across the inner sphere, in which case an electrostatic approximation can be applied [40]. In this regime, the interaction between the dipole and the surrounding material is dominated by near-field coupling [37,49]. Within this approximation, the emitted power is determined by the local-field factor at the emitter position and is proportional to the squared electric-field amplitude $|\mathbf{E}|^2$, as discussed in Ref. [40]. The opposite behavior observed for the two refractive-index configurations as $r_{\text{inner}} \rightarrow 0$ arises from the dielectric contrast at the sphere boundary, which induces polarization charges that modify the local electric field at the emitter position [40]. For $n_1 < n_2$, the field produced by these polarization charges enhances the local field

and thus increases the emitted power. In contrast, for $n_1 > n_2$, the same mechanism reduces the local field at the emitter position and suppresses emission. To verify this explicitly, we studied the limit $r_{\text{inner}} \rightarrow 0$ by comparing the electrostatic predictions with full-wave simulations. Using the electrostatic approximation [40], which gives $P_{\text{em}}/P_{\text{ref}} = n_2(3n_2^2/(n_1^2 + 2n_2^2))^2$, we obtain $P_{\text{em}}/P_{\text{ref}} \approx 6.10$ for $n_1 = 1.5$ and $n_2 = 3.3$, and ≈ 0.29 for the reverse configuration. We then performed additional simulations with a refined mesh to yield numerically highly converged results in the full-wave modeling at the smallest $r_{\text{inner}} = 1$ nm considered. This modeling yielded values with less than 0.1% relative difference compared to the electrostatic values. This quantitative agreement confirms that, in the small-radius limit, the enhancement or suppression of the emission rate is governed by local-field effects, thereby validating the electrostatic approximation as an explanation of the full-wave results for small r_{inner} .

When $n_1 = 1.5$ and $n_2 = 3.3$, the emitted power transfers into an optically denser medium. As the radius grows and near-field interactions weaken, the system moves away from the electrostatic regime, and the emitted power starts to fluctuate periodically with r_{inner} due to far-field interference effects in the inner sphere. The relatively low refractive index of the core reduces optical confinement, since the refractive-index contrast favors field penetration into the surrounding high-index medium, weakening the localization of resonant modes and enhancing leakage into the surrounding high-index medium, thereby reducing effective coupling to radiative modes [15]. These oscillations arise from constructive and destructive interference of waves reflected at $r = r_{\text{inner}}$. Their spacing is mainly determined by the wave vector inside the inner sphere and scales approximately as $\Delta r_{\text{inner}} \approx \lambda/2n_1$. Therefore, the peaks are more widely spaced for the $n_1 = 1.5$ and $n_2 = 3.3$ configuration compared to the reverse case (which is discussed in the following paragraph). The weaker confinement also broadens the resonance linewidths and reduces both the contrast and the peak amplitudes, reflecting increased radiative leakage into the surrounding medium. Consequently, the peak Purcell factor is lower compared to the case when $r_{\text{inner}} \rightarrow 0$.

For the reverse case of $n_1 = 3.3$ and $n_2 = 1.5$, the emitted power propagates toward a less optically dense medium. As the radius increases and the system moves to the far-field regime, $P_{\text{em}}/P_{\text{ref}}$ again exhibits periodic oscillations as a function of r_{inner} . Compared with the previous case, these oscillations are more closely spaced, and resonances are sharper and higher in contrast. Thus, in this spherical geometry, n_1 primarily governs the spacing of the resonances, while the refractive-index contrast controls their linewidth and peak amplitudes, providing a simple design rule for selecting either a sparser, smoother spectrum or a denser, sharper one. These behaviors are not restricted to the specific values for refractive index considered here but apply more generally in the present spherical geometry. The small-radius behavior is characterized by the electrostatic local-field correction associated with the dielectric contrast, whereas the larger radius response is controlled by resonances, optical confinement, and radiative leakage, with the quantitative details depending on r_{inner} , n_1 , and n_2 . Next, we include absorption [with $\text{Im}(n) = 0.01$] in the outer sphere. In Fig. 3, we show P_{em} calculated at both the surface of the inner sphere [r_{inner} , panels (a) and (c)] and at the surface of the outer sphere [r_{outer} , panels (b) and (d)]. Significant differences emerge between P_{em} calculated for these two cases. For small r_{inner} , the emitted power of the dipole (given by P_{em} extracted from the sphere at r_{inner}), increases sharply, as expected from the rapidly growing near field of a point dipole as $r \rightarrow 0$ [50]. The corresponding local absorption rate is proportional to $|\mathbf{E}|^2$, which in the point-dipole model scales roughly as $1/r^6$ when approaching the dipole (i.e., when $r \rightarrow 0$) [51]. Such a rapid increase in absorption occurs even for the small $\text{Im}(n) = 0.01$, which corresponds to a relatively long absorption length ($\sim 8.5 \mu\text{m}$) for far-field radiation (i.e., for a plane wave).

Classical dipole theory also shows [51] that the radial component of the time-averaged Poynting vector is dominated by a strongly localized near-field component close to the dipole. Integration over a spherical surface at r_{inner} yields for the emitted power an approximate scaling $\sim 1/r_{\text{inner}}^4$ for $r_{\text{inner}} \ll \lambda$. As r_{inner} increases, the influence of these near-field contributions diminishes, and the remaining variation of P_{em} reflects far-field absorption in the surrounding medium. Figure 4 shows $P_{\text{em}}/P_{\text{ref}}$

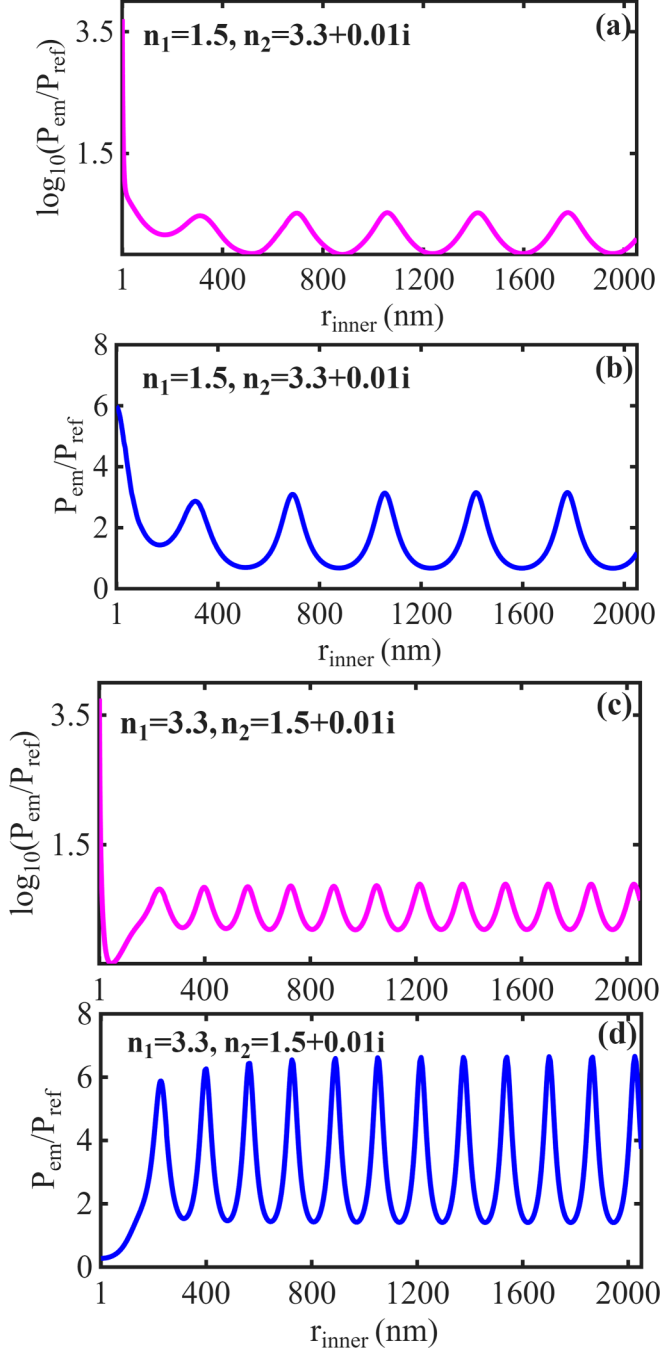


FIG. 3. (a) $\log_{10}(P_{\text{em}}/P_{\text{ref}})$ calculated at r_{inner} ; (b) $P_{\text{em}}/P_{\text{ref}}$ calculated at r_{outer} with $n_1 = 1.5$ and $n_2 = 3.3 + 0.01i$; (c) $\log_{10}(P_{\text{em}}/P_{\text{ref}})$ calculated at r_{inner} ; and (d) $P_{\text{em}}/P_{\text{ref}}$ calculated at r_{outer} for $n_1 = 3.3$ and $n_2 = 1.5 + 0.01i$ as a function of inner radius from 1 to 2050 nm.

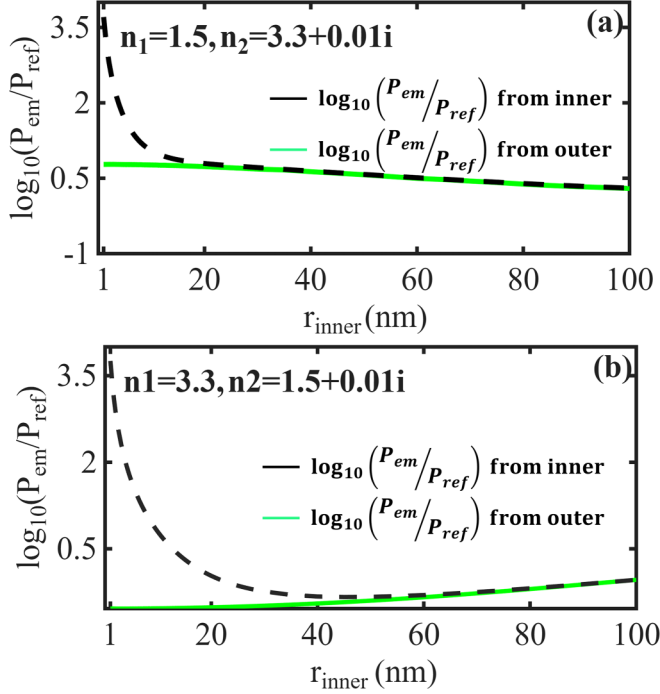


FIG. 4. $\log_{10}(P_{em}/P_{ref})$ vs r_{inner} (1–100 nm) in the near-field regime, comparing P_{em} calculated at r_{inner} and r_{outer} . (a) $n_1 = 1.5$ and $n_2 = 3.3 + 0.01i$ and (b) $n_1 = 3.3$ and $n_2 = 1.5 + 0.01i$. Data are extracted from Fig. 3.

from Fig. 3, enlarged on $r_{inner} < 100$ nm, shown for comparison in the same graph for extraction both at r_{inner} and r_{outer} . The difference between P_{em}/P_{ref} evaluated at r_{inner} and r_{outer} reflects the power absorbed in the lossy surrounding medium. Notably, in the near-field regime, the variation of P_{em}/P_{ref} with r_{inner} does not follow a single power-law dependence.

This behavior indicates that the emitted power at small distances is influenced by multiple components of the dipole field. This observation is consistent with that of a classical dipole, in which the electromagnetic field of a point dipole contains contributions scaling approximately as $1/r^3$, $1/r^2$, and $1/r$ [51]. The FEM simulations solve the full Maxwell equations for the dipole source, inherently including all these contributions.

For small r_{inner} , near-field absorption is strong, with the onset depending on the refractive-index contrast: For $n_1 = 1.5$ and $n_2 = 3.3 + 0.01i$, absorption dominates below approximately 20 nm, while for the opposite contrast, $n_1 = 3.3$ and $n_2 = 1.5 + 0.01i$, it occurs below roughly 40 nm. In these ranges, the dipole's evanescent near-field couples strongly to the absorbing region, leading to enhanced near-field absorption—analogueous to quenching phenomena reported for emitters near absorbing interfaces [52], where local dissipation can exceed the power emitted into the far field. As r_{inner} increases, near-field coupling diminishes and far-field optical energy transfer dominates. In this regime, the emitted power at r_{outer} closely represents the radiative power that would reach the far field, while absorption in the surrounding medium remains small, causing the curves for extraction at r_{inner} and r_{outer} to converge. This behavior is especially relevant for optoelectronic devices, where separating near-field interactions from far-field radiation is essential for analyzing photon recycling and optimizing overall device efficiency.

As seen in Fig. 4, at distances below roughly 30 nm from the dipole emitter, strong near-field interactions provide an additional pathway for photon recycling via the near-field absorption, increasing the probability that emitted energy is reabsorbed within the device before escaping. Understanding this reabsorption behavior is crucial for determining how much energy is effectively

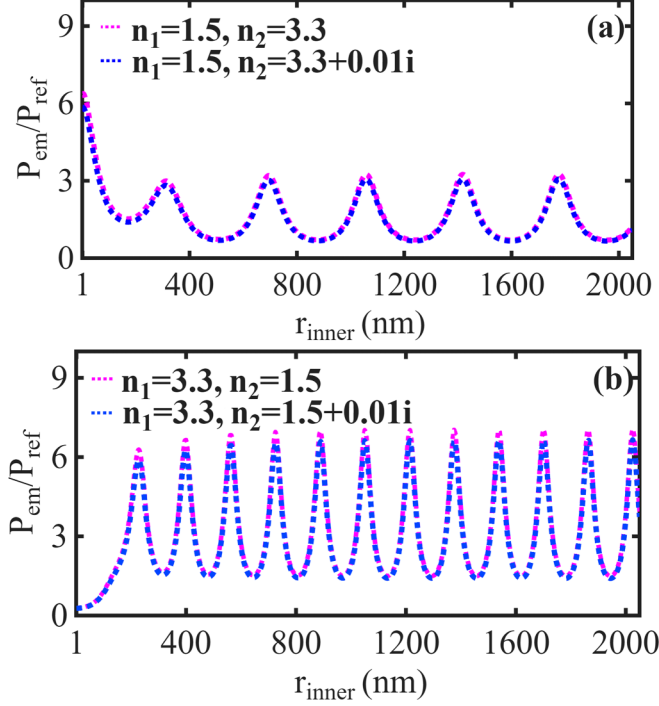


FIG. 5. $P_{\text{em}}/P_{\text{ref}}$ from P_{em} calculated at r_{outer} for (a) $n_1 = 1.5$ and $\text{Re}(n_2) = 3.3$ in nonabsorbing and absorbing media, and (b) $n_1 = 3.3$ and $\text{Re}(n_2) = 1.5$ in nonabsorbing and absorbing media, as a function of inner radius from 1 to 2050 nm (data from Figs. 2 and 3).

recycled versus radiated from the device. Our analysis offers insight into photon recycling that complements existing studies focused on overall device performance [25,53,54]. As a further demonstration of the transition between near-field and far-field optical energy transfer, Fig. 5 compares results for absorbing and nonabsorbing surrounding media (i.e., data extracted from Figs. 2 and 3).

Here, P_{em} for the absorbing surrounding medium is calculated at r_{outer} . The results for $P_{\text{em}}/P_{\text{ref}}$ for the absorbing case agree well with the results for the nonabsorbing case—except for slightly lower values due to absorption of far-field radiation over the bulk absorption length of $8.5\ \mu\text{m}$, before reaching r_{outer} . Thus, the magnitude of this deviation depends on the exact radius at which P_{em} is evaluated. Additional minor differences arise from weak changes in light scattering due to the nonzero imaginary part of the refractive index.

To summarize, although strongly increasing near-field absorption is observed as $r_{\text{inner}} \rightarrow 0$ in Figs. 3(a) and 3(c), this effect is confined to the small-separation regime and does not affect the physical definition and robustness of the far-field radiation studied in Fig. 5. Thus, in our fixed-amplitude dipole-moment model, near-field coupling modifies local absorption without necessarily producing a comparable reduction in the radiated power. This distinction is relevant for understanding energy transfer in optoelectronic devices and could guide studies of photon recycling in solar cells [55] and light out-coupling from LEDs.

As an alternative to using the above nonabsorbing region of $r < r_{\text{inner}}$ around the dipole, we also examined the case of a homogeneous medium with $\text{Re}(n_1) = \text{Re}(n_2)$ and $\text{Im}(n_1) = \text{Im}(n_2) = 0.01$ (not shown). Even when absorption was allowed all the way to the emitter in this way, causing a strong increase in near-field absorption (limited only by the meshing resolution in our FEM implementation), $P_{\text{em}}/P_{\text{ref}}$ calculated from r_{outer} remained finite and well behaved. This result

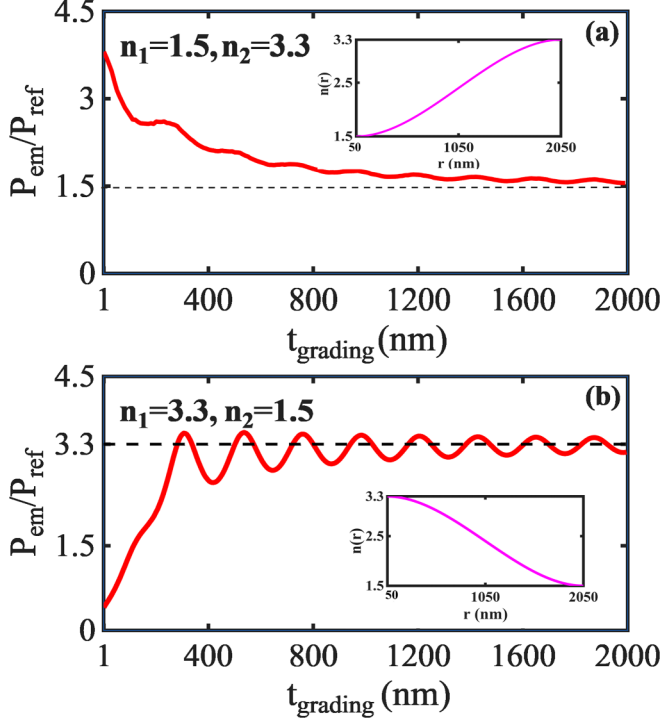


FIG. 6. $P_{\text{em}}/P_{\text{ref}}$ from P_{em} calculated at r_{inner} , with graded refractive-index transition, (a) $n_1 = 1.5$ and $n_2 = 3.3$, and (b) $n_1 = 3.3$ and $n_2 = 1.5$ as a function of grading thickness. Here, $r_{\text{inner}} = 50$ nm. The insets in panels (a) and (b) show for $t_{\text{grading}} = 2000$ nm the spatial profiles of the refractive index, varying smoothly from 1.5 to 3.3 and from 3.3 down to 1.5, respectively (see Sec. II for details).

indicates that the emitter can be embedded fully in the absorbing medium in the simulations without compromising the definition of the far-field radiation.

In this scenario, the total power supplied by the fixed-amplitude dipole moment naturally increases in response to the additional near-field losses, which in our model allows the radiative power reaching the far field to be maintained.

While the present work does not aim to provide a fully microscopic treatment of the emission from a dipole embedded in an absorbing continuum, it clarifies the emission properties of a dipole in a nonabsorbing dielectric surrounded by an absorbing medium and demonstrates the stability of the far-field radiation.

B. Emission from the center of a graded-index nanosphere

Here, we consider the effect of a graded-index transition, of thickness t_{grading} , when transitioning from n_1 to n_2 , in contrast to the abrupt refractive-index changes discussed above, which produced the sharp, repeated peaks in emitted power due to reflections at the interface. As seen in Fig. 6 for nonabsorbing surrounding medium, with a thick enough graded transition, the fringes in the emission power decrease since reflection and refraction effects diminish due to the adiabatic transition in refractive index.

The spacing of the fringes is set by the optical thickness of the graded region. With increasing grading thickness, the refractive-index contrast is distributed over a longer spatial scale, which reduces reflection at the transition. As a result, the peaks become less sharp, and both their amplitudes and contrast decrease. For grading thicknesses on the order of the wavelength, the fringe structure is strongly suppressed.

Interestingly, regardless of the relative values of n_1 and n_2 , $P_{\text{em}}/P_{\text{ref}}$ tends toward the value of n_1 as t_{grading} increases. This value corresponds to that of a dipole in a homogeneous n_1 surrounding. Thus, even if $n_2 < n_1$, with thick enough grading region, the emission from the dipole into the lower-refractive index surrounding medium occurs as if the dipole was in an infinite medium of n_1 . This is consistent with the classical result for a dipole near a planar mirror or dielectric interface, where at sufficiently large distances from the interface, emission approaches that of a dipole in an unbounded homogeneous medium [52]. Therefore, the lower-refractive index of the surrounding medium does not limit the emission from a dipole residing in an inner sphere of higher refractive index. This observation is interesting in the context of the typical discussion on the LDOS in media with different refractive indices [56]. These results indicate that the grading thickness influences the emission characteristics of the system: Thinner graded regions preserve more pronounced oscillatory behavior with larger peak amplitudes and contrast, while thicker graded regions reduce these oscillations and produce a smoother emission profile. This behavior also connects to the concept of total internal reflection (TIR), which typically limits out-coupling from a planar LED [57]. In planar geometries, TIR occurs when light tries to pass from a high-refractive-index material to a lower-index medium at angles beyond the critical angle, trapping light inside the high-refractive-index material. However, in spherical geometries, as here, the emitted light propagates radially outward and encounters either a gradual refractive-index transition or propagates at normal incidence to an abrupt interface, so the TIR condition is never met. These cases allow for more efficient light escape. These findings align with previous works in photovoltaics, where graded-index structures have been utilized to suppress reflections at material boundaries [58,59], leading to improved out-coupling of the emitted light and enhanced absorption within the active layer due to reduced reflection losses.

In Fig. 7, the response of the system in absorbing media and the emitted power across the surface of all three spheres—inner (at r_{inner}), graded (at $r_{\text{inner}} + t_{\text{grading}}$), and outer (at r_{outer})—are presented. The values for $P_{\text{em}}/P_{\text{ref}}$ from $r_{\text{inner}} + t_{\text{grading}}$ are lower than the values from r_{inner} due to absorption in the region with grading index.

Similarly, values for $P_{\text{em}}/P_{\text{ref}}$ from r_{outer} are lower than the values from $r_{\text{inner}} + t_{\text{grading}}$ due to absorption in the outer sphere. When the graded-index sphere becomes thicker, energy attenuation occurs more gradually because both the real and imaginary parts of the refractive index vary smoothly across the transition region. Therefore, reflection and refraction effects are reduced, and the overall behavior follows a smooth curve. Similarly, as for the case of nonabsorbing medium, also here, we find that $P_{\text{em}}/P_{\text{ref}}$, calculated at r_{inner} , tends toward the value of n_1 as t_{grading} increases. In contrast to the graded transition, the abrupt case exhibits strong fluctuations over the radius range considered here.

C. Effects from off-centered emitter

To address the practical utility of these findings for realistic optoelectronic devices where emitters are distributed throughout a volume, we conduct a spatial sensitivity analysis by shifting the dipole radially outward from the center (r_{shift}). Off-center placement breaks the spherical symmetry of the problem, making the emission behavior inherently dependent on both the emitter's position and its dipole moment orientation. We therefore distinguish between a radial orientation, where the dipole moment is aligned with the direction of displacement from the sphere center, and a transverse orientation, where the dipole moment is perpendicular to the radial displacement direction. The two perpendicular orientations are equivalent because of the remaining rotational symmetry of the geometry.

Figure 8 displays $P_{\text{em}}/P_{\text{ref}}$ for the two dipole orientations as a function of the normalized dipole displacement for both the abrupt transition with $r_{\text{inner}} = 250$ nm and the graded-index case with $t_{\text{grading}} = 500$ nm. The dipole was displaced up to $r_{\text{shift}} = 245$ nm for the abrupt interface and up to $r_{\text{shift}} = 45$ nm for the graded-index structure. These maximum normalized displacements are approximately 0.98 and 0.9, respectively.

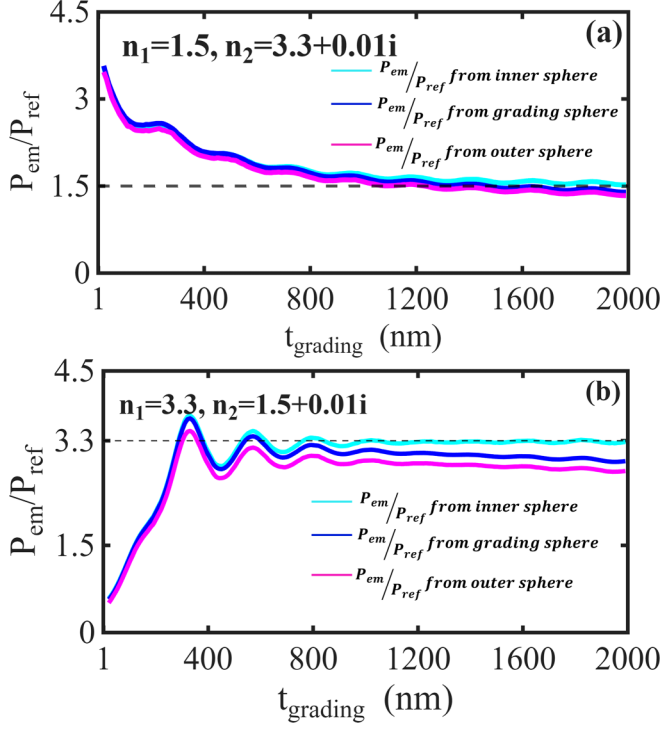


FIG. 7. P_{em}/P_{ref} for absorbing media with graded refractive index (a) $n_1 = 1.5$ and $n_2 = 3.3 + 0.01i$, and (b) $n_1 = 3.3$ and $n_2 = 1.5 + 0.01i$ as a function of grading thickness. Here, $r_{inner} = 50$ nm, and the results are shown for P_{em} calculated at r_{inner} , $r_{inner} + t_{grading}$, and r_{outer} . The dashed line shows the value of n_1 .

The abrupt-interface system exhibits a rather pronounced dependence on both dipole position and dipole orientation. For a radially oriented dipole, where the dipole moment is parallel to the displacement direction, the emitted power remains relatively insensitive to small displacement close to the center, up to a shift of approximately 50 nm, corresponding to $r_{shift}/r_{inner} \approx 0.2$. However, for the transverse orientation, where the dipole moment is perpendicular to the displacement direction, noticeable variations are observed for smaller displacements, even below $r_{shift}/r_{inner} \approx 0.1$. As the dipole moves closer to the abrupt interface, the emitted power changes strongly for both radial and transverse orientations. For $n_1 = 1.5$ and $n_2 = 3.3$ configuration, P_{em}/P_{ref} increases near the interface, particularly for the radial orientation. In contrast, for the $n_1 = 3.3$ and $n_2 = 1.5$ system, P_{em}/P_{ref} decreases substantially as the dipole approaches the interface. We assign this behavior to the sharp refractive-index discontinuity, which modifies the local optical environment and the coupling of the dipole emission to the available optical modes.

For the graded-index structure, as shown in Figs. 8(c) and 8(d), the emitted power varies weakly with dipole displacement for both radial and transverse dipole orientations across the entire evaluated displacement range and for both refractive-index configurations.

This shows that the graded-index transition strongly reduces the dependence of the emission response on the exact dipole position and orientation. Therefore, the smoothing effect is not restricted to the idealized centered-dipole configuration but remains robust for off-center emitters within the considered region. This supports the practical relevance of the graded-index transition for distributed emitters in optoelectronic structures.

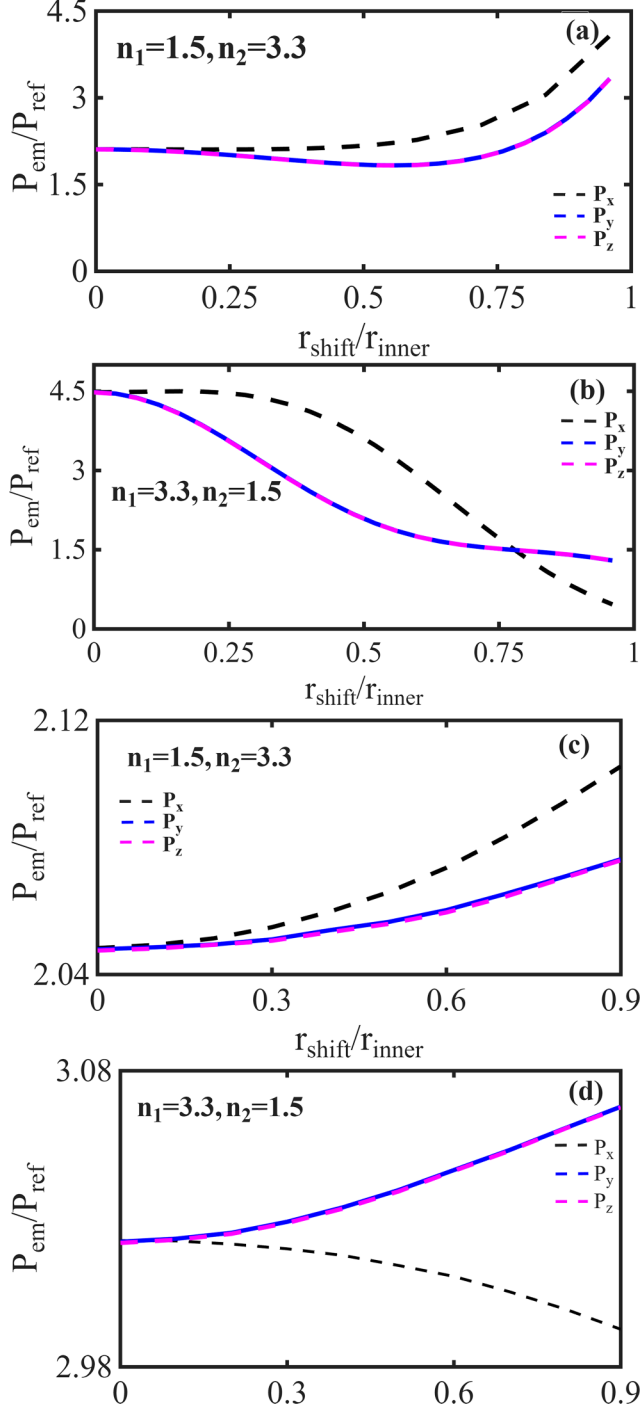


FIG. 8. $P_{\text{em}}/P_{\text{ref}}$ from P_{em} calculated at r_{inner} as a function of $r_{\text{shift}}/r_{\text{inner}}$ for off-center dipoles (here, the x direction is parallel to the radial displacement direction, with y and z the two perpendicular directions to the radial displacement direction). Abrupt transition in refractive index at $r_{\text{inner}} = 250$ nm with (a) $n_1 = 1.5$, $n_2 = 3.3$, and (b) $n_1 = 3.3$, $n_2 = 1.5$. Graded-index transition with $t_{\text{grading}} = 500$ nm and $r_{\text{inner}} = 50$ nm for (c) $n_1 = 1.5$, $n_2 = 3.3$, and (d) $n_1 = 3.3$, $n_2 = 1.5$.

D. Continuous semiconductor region versus discrete two-level system

Before concluding, it is worth pointing out an important distinction between photon recycling in a continuous semiconductor region and modified emission from a discrete two-level (atomic) system due to parasitic absorption in the surrounding. In a continuous semiconductor, photon recycling leads to a re-excitation of electrons to the conduction band from the valence band, thus without net loss of energy for the system [55]. In contrast, for a two-level atom, parasitic absorption acts as a loss channel that reduces external quantum efficiency (i.e., no photon recycling occurs). In our fixed-amplitude dipole-moment model, the source supplies the additional power required to maintain its oscillation strength, such that the radiated power reaching the far field is affected only weakly despite local absorption losses. We emphasize, however, that the present treatment is an electromagnetic model of a driven source and does not constitute a full microscopic description of quenching or dissipative emission processes in real atoms, molecules, or quantum dots. In this sense, the present model is qualitatively closer to an idealized photon recycling in semiconductors, where the local absorption contributes to re-excitation processes, rather than to a microscopic description of emission from a discrete quantum emitter in a parasitically absorbing environment.

IV. CONCLUSION

We have numerically investigated light emission from a dipole in an inner spherical domain of refractive index n_1 , considering both nonabsorbing and absorbing surrounding media of refractive index n_2 with inhomogeneous refractive-index distributions—either with abrupt changes at layer boundaries or with smooth radial variation $n(r)$. An abrupt transition in the refractive index between the inner and outer regions leads to sharp, repeated peaks, as a function of the radius of the inner sphere, in the emitted power from the dipole, due to reflection effects from the interface. In contrast, systems with a graded variation in the refractive index exhibit smoother peaks as the thickness of the graded region increases. Since the refractive index varies continuously from n_1 to n_2 across the graded region, increasing its thickness reduces the gradient (i.e., change per unit length), thereby diminishing reflection effects. With absorbing material in the surrounding sphere, the emitted power from the dipole, as calculated through the surface of a sphere at r_{inner} , increases strongly as the inner radius decreases, due to near-field absorption. For larger r_{inner} , near-field absorption is negligible, and the emission follows closely that in a nonabsorbing surrounding medium.

Importantly, for the refractive-index contrast considered here [$\text{Im}(n_2) = 0.01$], strong near-field absorption mainly increases the fraction of the dipole's emitted power that is dissipated in the surrounding medium, while the radiated power propagating outward is affected only weakly compared to the nonabsorbing case. This behavior is evidenced by the strong dependence of the power extracted at r_{inner} for very small dipole-medium separations, while the power extracted at r_{outer} , which represents radiation leaving the system, varies only weakly with r_{inner} . The difference between the powers evaluated at r_{inner} and r_{outer} corresponds to energy absorbed in the surrounding medium. This distinction is important for analyzing internal optical energy transfer and absorption processes in optoelectronic devices, such as photon recycling in the active semiconductor region in solar cells.

An interesting observation from our study is that in the graded systems, regardless of whether $n_1 < \text{Re}(n_2)$ or $n_1 > \text{Re}(n_2)$, the ratio $P_{\text{em}}/P_{\text{ref}}$ tends toward the value of n_1 as the grading thickness increases. This shows that even if $n_1 > \text{Re}(n_2)$, a sufficiently thick grading region allows the emission from the dipole to behave as though it was in an infinite n_1 medium, and thus not limited by the refractive index of the surrounding medium. Thus, graded refractive index enables smooth control of light emission in both absorbing and nonabsorbing systems, supporting practical applications in photovoltaics [30,60], LEDs [61], and other optoelectronic devices. By addressing key challenges such as reflection losses and TIR, these findings provide a pathway toward optimizing light-matter interactions and advancing optical performance in future photonic devices.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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