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On-Demand Single-Photon Extraction for Underwater Quantum Communication

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ABSTRACT: Single-photon sources with high repetition rates have been a focal point of modern research for decades. However, their application in underwater environments is significantly limited due to the absorption properties of water, which hinder the propagation of most optical wavelengths. This study addresses the challenge by reporting on-demand single-photon extraction suitable for underwater quantum communication. The use of plasmonic nanoantennas can significantly enhance the spontaneous emission of single-photon sources. Nonetheless, a primary challenge is the nanoscale guiding of emitted photons in underwater environments. To overcome this, a more sophisticated design is required to enhance photon emission and achieve momentum matching with water. Here, we present a topology-optimized design of underwater plasmonic nanoantennas to mitigate these limitations. The nanoantenna consists of an optimized gold pattern and a silicon nitride substrate. Consequently, the normalized extraction decay rate (γ_e/γ_0) can reach 4.02 at a wavelength of 517 nm, which is within the blue-green spectral range, when using an objective lens with a numerical aperture of 0.6 (cross-section angle of 26.7°). The proposed design approach for plasmonic nanoantennas is versatile and holds promising potential for various applications, particularly in advancing single-photon technologies for quantum communication.

1. INTRODUCTION

Single-photon sources with high repetition rates are increasingly demanded for fast and secure underwater quantum communication [1–3]. Traditionally, underwater communication employs longitudinal acoustic waves [4], which are effective for ultra-long-distance communication [5, 6]. However, these waves are inherently insecure, omnidirectional, and exhibit low data rates, particularly over long distances. [7, 8]. For applications involving shorter distance [9–11], standard light sources are more advantageous due to their higher data transmission rates and enhanced security [12, 13]. While radio and infrared waves are effective for long-distance communication on land [14, 15], they are impractical underwater due to absorption properties. To enable underwater communication using light sources, a special wavelength is required [16]. Although most optical wavelengths are absorbed and scattered in water, blue and green light can penetrate more effectively due to their lower absorption in these spectral ranges [16].

A well-established solution has been identified to address these problems: plasmonic metamaterials, including nanopatch antennas [17, 18], hyperbolic metamaterials [19–21], and photonic hypercrystals [22, 23]. These structures have recently demonstrated significant local field enhancement, enabling the generation of single photons from quantum emitters at high repetition rates, surpassing traditional dielectric photonic resonators [24]. According to the Purcell effect [25, 26], plasmonic metamaterials, which could form an ultrasmall effective mode volume, are predicted to achieve emission rate speed-up into the terahertz (THz) regime, comparable to the decoherence rate of most solid-state emitters at room temperatures. However, a key challenge with plasmonic metamaterials is the nanoscale coupling of emitted photons for underwater quantum communication. The difficulty lies in balancing the need for a small mode volume to speed up emission with the requirement for a sufficiently large mode volume to ensure efficient extraction [27]. Few proposals have been made to enhance the photon extraction decay rate using plasmonic metamaterials, such as metallic structures supporting gap surface plasmons integrated with phase-matched nanofibers [28], nanopatch antennas [17, 18], and patterned hyperbolic metamaterials [19–21]. However, these attempts are generally considered impractical or inefficient for achieving single-photon extraction using a water collection pathway. Therefore, a more sophisticated approach is necessary, involving the enhancement of high-k (i.e., high-wavevector) eigenmodes [29] within plasmonic metamaterials to improve photon emission and achieve momentum matching with water.

This study aims to employ a topology-optimized design for underwater plasmonic nanoantennas and analyze their performance using a water collection pathway. Inspired by recent advances in topology optimization (TO) for efficient and coherent light-matter interactions [30–32], we apply a density-based TO framework to optimize single-photon sources. Consequently, the plasmonic nanoantenna, designed for underwater quantum

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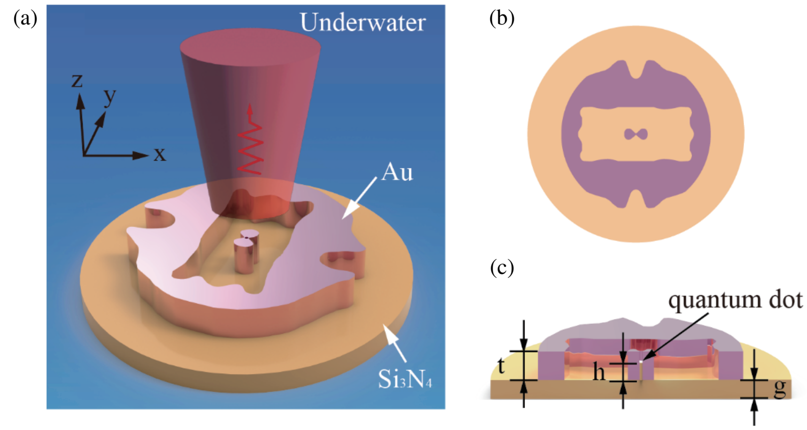

FIGURE 1. Schematic of a topology-optimized design of underwater plasmonic nanoantennas. (a) The structure consists of an optimized gold (Au) pattern on a silicon nitride (Si_3N_4) ubstrate. (b) Top view of the nanoantenna. (c) The cutaway view of the nanoantenna, where $t = 120$ nm and $g = 80$ nm. A quantum dot is positioned within the nanohole, $h = 80$ nm away from the substrate.

communication, consists of an optimized gold (Au) pattern and a silicon nitride (Si_3N_4) substrate (Figure 1). The center of the Au pattern features a nanopore matching the diameter of a quantum dot, which is used to position the quantum dot. Specifically, the omnidirectional far-field spontaneous emission from quantum emitters can be collected using high numerical aperture (NA) optics (as mentioned in general underwater collection pathway [33]). The collected power is calculated as an integral over a circular area above the emitter, mimicking a water collection pathway by a commercially available objective lens with an NA of 0.6 ($NA = n \cdot \sin\alpha$, cross-section angle α of $26.7°$). As a result, the extraction decay rate (γ_e) can reach $4.02\gamma_0$ while the Purcell factor exceeds $3200\gamma_0$, where γ_0 is the spontaneous emission decay rate of quantum emitter in free space.

2. METHODS AND RESULTS

We start with the numerical modelling using the commercial finite element solver COMSOL Multiphysics. Following previous work [32], TO could be employed to design the plasmonic nanoantenna within a design region situated directly on top of the substrate with a radius of 500 nm. Due to the differences in underwater refractive indices and radiation modes, previously designed plasmonic nanoantennas are no longer effective. The proposed design features an optimized Au pattern grown on a Si_3N_4 ($\varepsilon_{Si_3N_4} = 4.12$) substrate, with water (refractive index of 1.33) as the background [34] (see Figure 1(a)). The dielectric constant of Au is derived from the experimental data [35]. Figure 1(c) shows that a quantum dot (CdSe/ZnS core-shell and $\varepsilon_{ZnS} = 5.81$) [36] with a emission wavelength of 517 nm is embedded in the central nanohole ($d = 12$ nm) of the Au pattern, where gap plasmon resonance can occur. In order to accommodate quantum dots, Si_3N_4 is filled underneath. To estimate photon emission and extraction from quantum dots, the following assumptions are applied. First, we assume that the light-matter interaction within the plasmonic nanoantenna operates in the weak-coupling regime [37], meaning that the non-radiative damping of single-photon sources are greater than the interaction strength between the quantum dots and the plasmonic nanoantenna. This assumption aligns well with classical electrodynamics principles [38]. Second, the quantum dot in this study is modeled as an oscillating classical point dipole within a dielectric host with its polarization direction parallel to the x-axis.

In many applications of quantum information processing, the overall photon extraction rate is a critical factor [39]. This rate increase with the photon emission rate, which is proportional to the Purcell factor F_P, and the photon collection efficiency. In this study, we focus on improving the overall photon extraction rate, rather than optimizing the emission rate or collection efficiency separately. Thus, the objective of our TO is to enhance the far-field photon extraction decay rate through an objective lens with an NA of 0.6. The normalized extraction decay rate is defined as the ratio of the power emitted by the dipole source to the collection surface of the objective lens, relative to the total radiation power in free space, that is $\gamma_e/\gamma_0 = W_e/W_0$ [40]. By performing surface integration at the surface of the objective lens, the power of the photon extraction into the objective lens can be obtained, which is $W_e = \iint_F \mathbf{S} \cdot \hat{\mathbf{z}} dxdy$. The spontaneous emission rate and the total radiated power of a quantum emitter in free space are denoted as γ_0 and W_0, respectively. Furthermore, a quantum emitter in a plasmonic nanoantenna will experience an enhanced radiation rate compared to that in a homogenous medium, as given by the Purcell factor [41], which is $F_P = \gamma_{total}/\gamma_0 = W_{total}/W_0$, where γ_{total} represents the total photon emission rate, and the total emitted power W_{total} of the quantum emitter can be numerically computed as the integral of power flux through a spherical surface with a radius of 2 nm.

Similar to the analysis step in previous work [32], we set the material distribution in the optimization domain to be smooth, represented by the following permittivity function

$$\varepsilon(x, y) = \varepsilon_{water}[1 - \rho(x, y)] + \varepsilon_{Au}\rho(x, y), \quad \rho \in [0, 1] \quad (1)$$

The material density distribution $\rho(x, y)$ ranges from 0 to 1, where 0 represents water and 1 represents Au. Here, ε_{water}

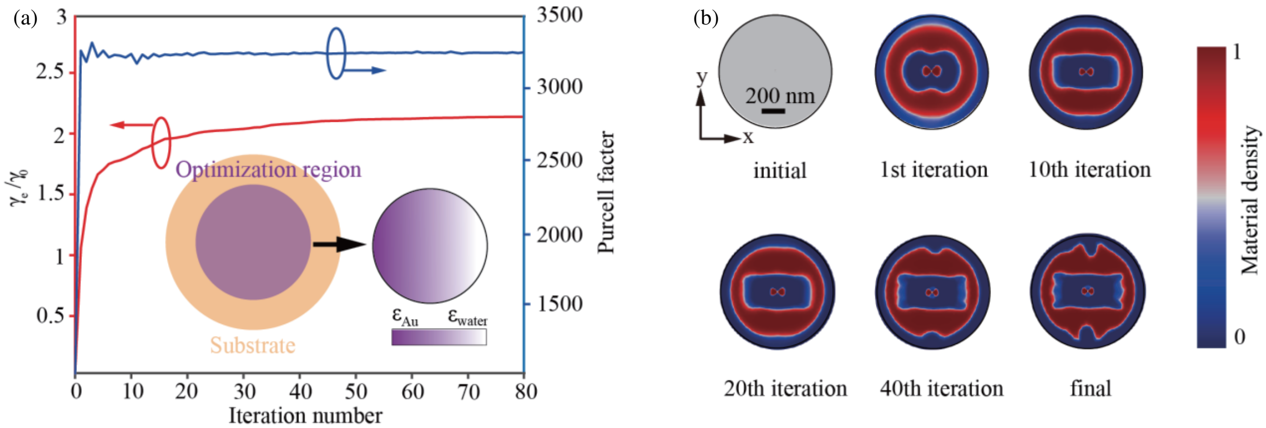

FIGURE 2. Analysis of topology optimization process. (a) The evolution of normalized extraction decay rate γ_e/γ_0 (marked in blue) and Purcell factor (marked in green) during TO operation. The chosen working wavelength of $\lambda = 517$ nm corresponds to the emission spectrum of CdSe/ZnS core-shell quantum dots, which lies within the blue-green spectral range. (b) During the optimization process, the material gradually approaches two-phase release.

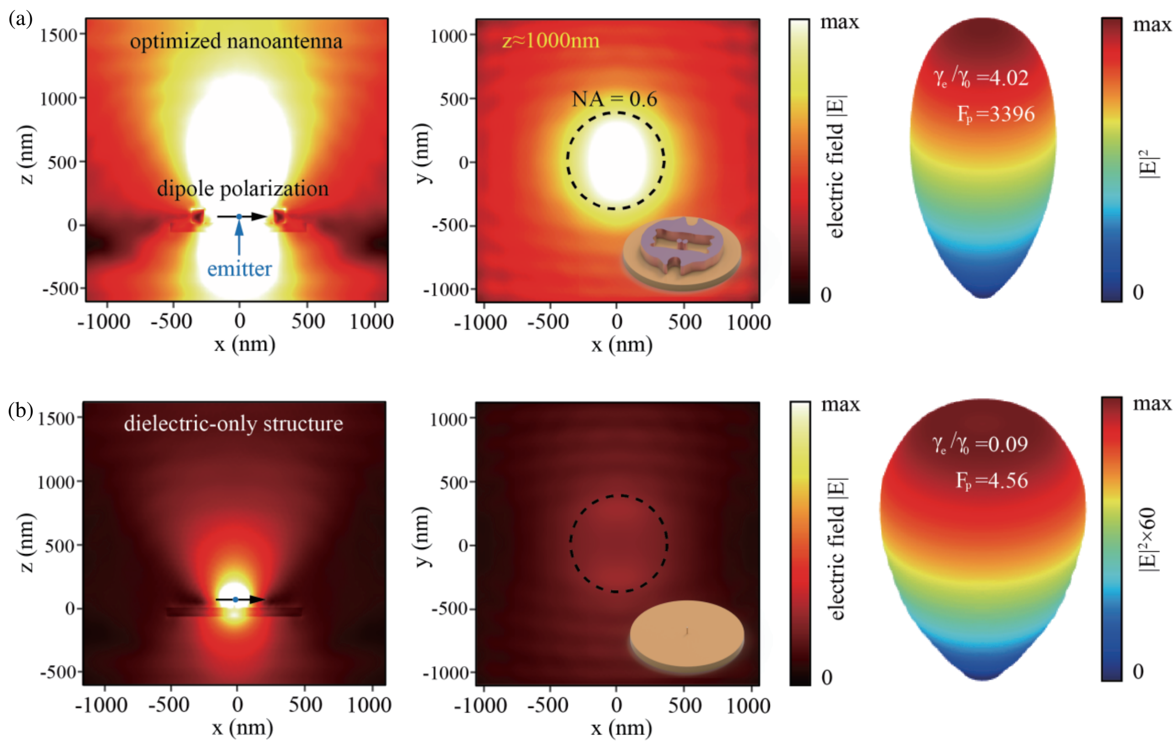

FIGURE 3. Performance Analysis of Optimized Nanoantenna. (a) The electric field in the xOz plane under the coupling of quantum dots and optimized plasmonic nanoantennas (left). The electric field distribution approximately 1 µm above the xOy plane (middle). Far-field emission patterns of the optimized plasmonic nanoantenna (right). (b) The electric field in the xOz plane under the coupling of dielectric-only structure (left). The electric field distribution approximately 1 µm above the xOy plane (middle). Far-field emission patterns of the nanostructures composed solely of dielectric materials (right).

and ε_{Au} denote the dielectric constants of water and Au, respectively. TO allows the relative dielectric constant of each discrete voxel in the design area to serve as a degree of freedom, forming a two-dimensional (2D) grid. The optimized distribution of 2D materials extends along the z-axis, leading to the creation of a topology-optimized plasmonic nanoantenna.

Figure 2(a) illustrates the convergence dynamics for a TO run, highlighting the evolution of coupling efficiency throughout the optimization process. The normalized extraction decay rate and Purcell factor increase progressively with the number of iterations and eventually approach a steady-state local solution. For illustrative purposes, a working wavelength of $\lambda = 517$ nm is selected corresponding to the emission spectrum of

CdSe/ZnS core-shell quantum dots within the blue-green spectral range [42]. The optimization begins with an initial material distribution of $\rho(x, y) = 0.5$ and converges to a binary material mode by the end of the cycle (Figure 2(b)). At this stage, the material density matrix is fully binarized by thresholding all voxels a process referred to as degradation [43]. During the optimization, the normalized extraction decay rate reaches 4.02, while the Purcell factor increases to 3200. Consequently, significant radiation fields are extracted into the objective lens, as depicted in Figure 3(a). A comparison between the electric field distribution of the optimized plasmonic nanoantenna (Figure 3(a)) and the dielectric-only structure (Figure 3(b)) reveals a substantial improvement in far-field photon extraction after optimization. Furthermore, Figure 3 indicates that the designed plasmonic nanoantenna can enhance radiation directionality to a certain extent. Therefore, topological optimization of the plasmonic nanoantenna is essential for effective underwater quantum communication.

3. CONCLUSION

In summary, we have designed a robust plasmonic nanoantenna for underwater quantum communication using a density-based TO framework. By utilizing the design flexibility of TO, our method effectively maximizes the advantages of traditional plasma and dielectric nanostructures while minimizing their weaknesses. Moreover, the proposed plasmonic nanoantenna and TO can achieve on-demand single photon sources for quantum photon networks and underwater quantum communication applications.

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