



Article

Modulating Photodissociation and Photobleaching via Plasmon Resonance to Enhance Light-Induced Nitric Oxide Release

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Abstract

Localized therapeutic action and targeted drug release offer compelling advantages over traditional systemic drug administration. This is particularly important for nitric oxide (NO), whose biological effects vary greatly depending on concentration and cellular environment. Light-sensitive NO donors are promising for achieving precise, on-demand NO release. However, their efficiency and photostability are limited by competing photo-physical processes and the generation of reactive oxygen species (ROS). In this study, we investigate hybrid systems composed of photosensitive nitric oxide (NO) donors and silver island films (SIFs). The influence of localized surface plasmon on non-radiative relaxation pathways and ROS generation is the main focus of the paper. Upon excitation at 500 nm, we observed several-fold increase in NO release, attributed to resonant interactions between the plasmonic field and the dye molecules. By tuning the thickness of a SiO₂ buffer layer, we identified key parameters affecting process efficiency: the spectral overlap between the plasmon resonance and the sensitizer's absorption band, and the distance between the nanoparticle and the molecule. Additionally, singlet oxygen generation increase was observed. These findings demonstrate the potential of plasmonic enhancement to controllably boost photochemical activity in organic systems, paving the way for advanced applications in phototherapy and biomedical diagnostics.

Keywords: localized plasmon resonance; nitric oxide donor; photodissociation; singlet oxygen



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1. Introduction

Modern society faces global health challenges, including the high mortality rate associated with cancer. One promising approach to address these threats is photodynamic therapy (PDT), which relies on the generation of reactive oxygen species (ROS), particularly singlet oxygen (¹O₂). This highly reactive species can induce oxidative damage to cellular components and trigger apoptosis, making it a powerful tool in the localized treatment of tumors and infections [1]. The production of ¹O₂ occurs upon photoexcitation of a sensitizer followed by its interaction with molecular oxygen. The efficiency of this process depends on the quantum yield of intersystem crossing and the physicochemical properties of the sensitizing system [2].

In recent years, there has been growing interest in combined therapeutic strategies that incorporate both reactive oxygen species (ROS) and nitric oxide (NO) donors. NO is a

short-lived signaling molecule that plays a crucial role in various physiological processes, including vascular tone regulation and immune response modulation. It plays a complex and sometimes contradictory role in cancer: low NO levels can promote tumor growth, angiogenesis, and metastasis, whereas high concentrations may exert cytotoxic or cytostatic effects, damaging tumor DNA, activating p53, and sensitizing cancer cells to chemo-, radio-, or immunotherapy. This duality makes NO both a potential tumor promoter and a promising therapeutic agent for resistant cancers [3]. The combination of singlet oxygen and NO enables a multi-mechanistic approach to target destruction, enhancing therapeutic efficacy—particularly in cases where resistance to conventional treatments has developed. Of particular interest are photochemical systems capable of simultaneously generating both active species, thereby producing a synergistic therapeutic effect [4–6]. In this context, precise control over the efficiency of $^1\text{O}_2$ and NO generation is essential.

The photochemical and photophysical properties of dye molecules can be modulated by introducing appropriate substituents, an approach recently explored for NO donors based on the boron-dipyrromethene (BODIPY) core [7]. Another promising strategy involves modifying the molecular environment by placing the dye in proximity to metal nanoparticles. Beyond their well-known role in enhancing fluorescence [8–10], plasmonic nanoparticles can also modulate non-radiative processes [11–13]. For example, in [11], the singlet oxygen yield was improved by varying the buffer layer thickness and modeling the effect theoretically. This dual enhancement enables not only increased singlet oxygen production but also the activation of photodissociation pathways responsible for NO release. This plasmon-enhanced nitric oxide release is a relatively new and less explored area. One of the key works in this field is [14], where excitation of the plasmon resonance in silver nanostructured “Quanta Plate” films led to a 2–6-fold increase in NO yield. However, in existing works, island-like metallic films with relatively broad plasmon resonances were used, and the precise position of the plasmon resonance was often not considered a critical factor. In our case, the silver island films (SIFs) used are distinct in that their plasmon resonance can be tuned to match the absorption band of the dye, allowing more precise control over the interaction between the plasmonic field and the photosensitizer.

In this work, we focus on the investigation of hybrid systems composed of photochemically active BODIPY-based NO donors integrated with silver island films (SIFs) [15]. These systems are designed to explore the role of localized surface plasmon resonances in modulating non-radiative relaxation pathways, such as intersystem crossing and photodissociation, and, consequently, the efficiency of $^1\text{O}_2$ and NO generation. Unlike prior works, our SIFs feature a distinct and narrow plasmon resonance, allowing us to directly demonstrate that the metal-enhanced photodissociation rate depends on the excitation wavelength. Such strategies are particularly valuable for creating spatially confined and controllable sources of reactive species—an essential feature given their short lifetimes and high reactivity.

We show that incorporation of SIF led to a pronounced enhancement of NO release at ~500 nm excitation (up to seven-fold) attributed to resonant coupling between the plasmonic field and the dye molecules. By systematically varying the thickness of a SiO_2 buffer layer, we identified key parameters that govern the overall efficiency of the system: namely, the spectral overlap between the plasmon resonance and the sensitizer’s absorption band, as well as the spatial separation between the nanoparticle and the donor molecule. Additionally, singlet oxygen production was enhanced by more than 2.5-fold with decreasing buffer layer thickness. These findings underscore the potential of plasmon-enhanced photochemistry to controllably amplify the therapeutic output of organic photoactive compounds, opening new avenues for applications in photodynamic therapy and biomedical diagnostics.

2. Materials and Methods

2.1. Silver Island Films (SIF)

Four types of SIFs with varying thicknesses of the silicon dioxide buffer layer were used in the experiment; their structures are schematically illustrated in Figure 1A. The films were prepared by the physical vapor deposition method in vacuum chamber PVD 75 system (Kurt J. Lesker, Dresden, Germany) using the procedure described in [15]. In brief, silver (99.99%) was deposited resistively from a tungsten boat onto the surface of glass substrates at a rate of $0.6 \text{ \AA/s}$ with a residual vapor pressure of 10^{-6} Torr and room temperature of the substrate. The equivalent thickness of the films was 10 nm. Next, the samples were annealed at a temperature of 200°C for 30 min. Silicon dioxide (99.99%) was deposited on top of the silver film using an electron beam evaporator at a rate of $0.1 \text{ \AA/s}$ under the same conditions. The effective thickness calculated from equal distribution of the material onto the surface was: 0.5 nm, 2 nm and 20 nm for three samples, respectively.

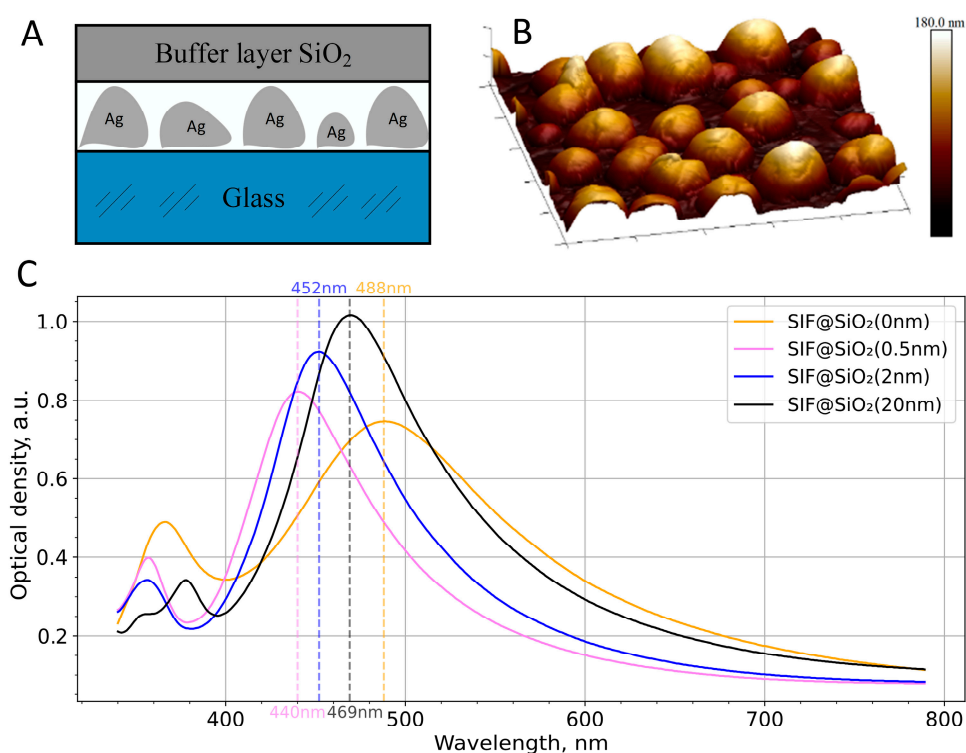


Figure 1. Silver island films (SIFs) used in experiments. (A). Schematic representation of SIFs coated with a silicon dioxide buffer layer. (B). Representative 3D-AFM morphology image of SIF without the SiO₂ buffer layer at area $5 \times 5 \mu\text{m}$, with vertical Z-color scale 180 nm and real dimensions of morphology scales X-Y-Z. (C). Extinction spectra of silver island films in air with varying thicknesses of the buffer layer.

The structure of silver islands obtained with atomic force microscopy (AFM) is visualized in Figure 1B. Morphology imaging was performed using atomic force microscope “Dimension Icon” (Bruker, MA, USA) in order to acquire information about size and shape of the nanoparticles. The soft probes ScanAsyst-Air (Bruker, MA, USA) with nominal tip radius 2 nm were used. Samples were scanned in resonant semicontact tapping mode of AFM (PeakForce™, Bruker, MA, USA) with tapping amplitude 100 nm and frequency 2 kHz. Scanning was performed for area $1 \times 1 \mu\text{m}$ with resolution 256×256 pixels (i.e., lateral pixel size $\sim 4 \text{ nm}$) and tip velocity $2 \mu\text{m/s}$. Post-visualization data treatment included only removal of the inclination angle with no further filtration of lines of scanning or mathematical smoothing.

Figure 1C shows the extinction spectrum of SIF without the buffer layer having a plasmon resonance at 488 nm (orange line), as well as three SIFs buffer layer thicknesses of 0.5 nm, 2 nm, and 20 nm having the plasmon resonances at 440 nm, 452 nm, and 469 nm, respectively. The spectra were obtained with a Shimadzu UV-1900 spectrophotometer equipped with halogen and deuterium lamps.

2.2. Photosensitive Nitric Oxide Donor

The BODIPY dye family represents a versatile class of molecules with broad applicability, including nitric oxide (NO) photorelease. In this study, we employ the compound shown in Figure 2, referred to as N1, which was synthesized according to a previously reported procedure [7]. An analogous compound lacking the NO-releasing group, designated as N0, was used as a control in our experiments.

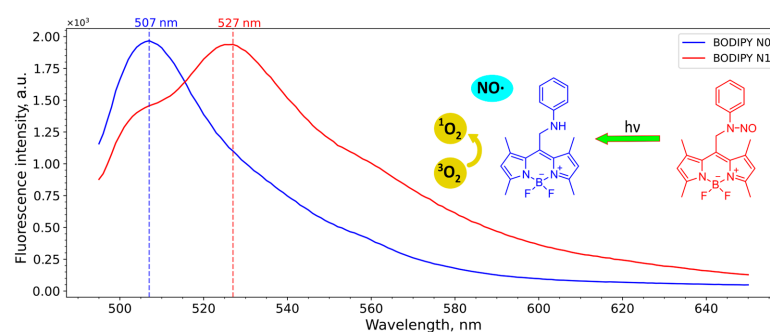


Figure 2. Chemical structures of BODIPY N1 and N0, the photorelease scheme and fluorescence emission spectra of both compounds.

Upon exposure to light with a wavelength of approximately 500 nm, BODIPY N1 undergoes photorelease of NO. This process is accompanied by a blue shift in both its absorption and fluorescence spectra. Figure 2 displays the fluorescence emission spectra of N1 (red line) and N0 (blue line), highlighting this shift.

The intrinsic fluorescence change provides a convenient self-reporting mechanism for real-time monitoring of NO release. In the photorelease experiments, the spectral blue shift is observed concurrently with an overall decrease in signal intensity, attributed to photobleaching.

2.3. Illumination Sources

LEDs with emission wavelengths of 400 nm and 500 nm were used to irradiate the samples. The diode current, used to control the output power, was varied in the range of 0.1–1 A. The normalized emission spectra of the LEDs, along with the absorption spectrum of BODIPY N1, are shown in Figure 3.

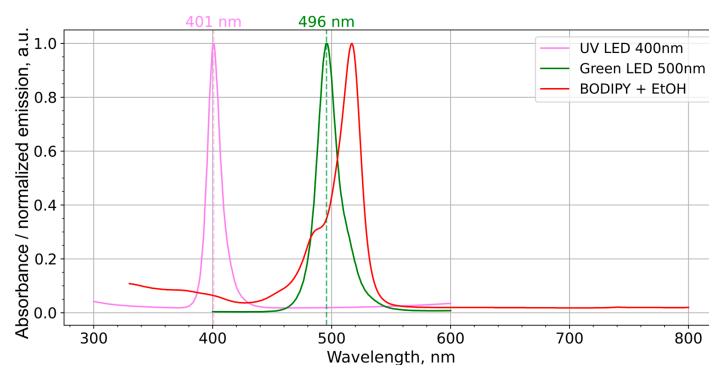


Figure 3. UV-Vis absorption spectrum of BODIPY N1 and emission spectra of LEDs used in photolysis experiments. All spectra are normalized to 1.

2.4. Experimental Setup

Plasmonic modulation of photochemical processes occur in the vicinity of nanoparticles. To ensure the closest possible contact between the NO donor molecules and the SIF, a droplet (8 μ L) of a 0.1 mM BODIPY solution in ethanol was sandwiched between the SIF and the clean cover glass (8 mm $\times$ 26 mm). The sample was then irradiated using LED source (Figure 4).

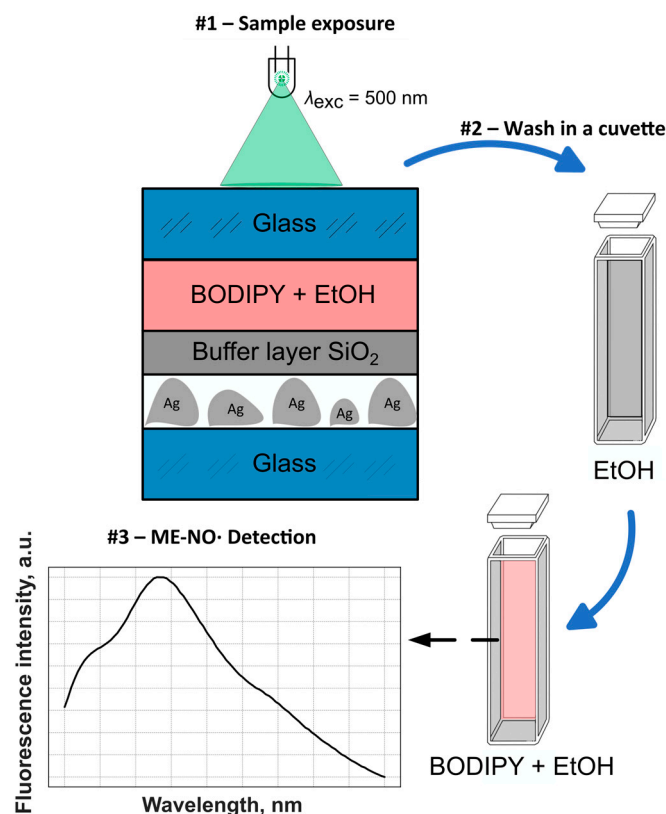


Figure 4. Scheme of the experiment.

After irradiation, the glass substrates with the samples were placed into a cuvette containing 3 mL of ethanol, thoroughly rinsed, and then the solution was analyzed using a spectrofluorometer (Shimadzu RF-6000). Fluorescence excitation wavelength was set to 480 nm, emission 495–650 nm.

2.5. NO Photorelease Detection

In this study, we initially explored the use of fluorescent molecular probes, such as DAR-2 [16], for NO detection. However, our experiments showed that these probes are highly sensitive to the presence of silver, even in trace amounts, which can significantly distort the results (see Appendix A).

Another approach commonly used for NO detection in photorelease experiments involves electrochemical sensors [17]. However, this method requires real-time detection of NO in relatively large sample volumes, which limited its applicability in our experimental setup.

In our case, samples were irradiated as thin liquid layers, then transferred to a cuvette and diluted for measurement. Within this context, the most convenient and reproducible method proved to be monitoring the intrinsic fluorescence of the BODIPY dye. Changes in both spectral position and intensity served as reliable indicators of the extent of photodissociation (NO release) and photobleaching. The spectra processing method consists of the following main steps:

A series of spectra obtained at different moments of time were analyzed in a fixed spectral range (usually 500–540 nm). For each spectrum, the position of the emission maximum was determined. In the vicinity of the spectral maximum ($\pm n$ points, where n is typically 4), the experimental data were locally approximated using a parabolic function of the form:

$$I(\lambda) = a(\lambda - \lambda_0)^2 + b(\lambda - \lambda_0) + c, \quad (1)$$

where $I(\lambda)$ is the fluorescence intensity, λ is the wavelength, and λ_0 is central wavelength. The location of the maxima were calculated as:

$$\lambda_{max} = -\frac{b}{2a}. \quad (2)$$

The uncertainty in determining the emission maximum was estimated using the covariance matrix of the fitting parameters. The sequence of $\lambda_{max}(t)$ values obtained from the series of spectra was interpreted as the kinetics of the fluorescence peak shift. In the initial part of the kinetics (typically the first 3–7 points), a linear fit of the $\lambda_{max}(t)$ dependence was performed using the least squares method. The slope of the fitted line was interpreted as the NO release rate, expressed in units of nm/s:

$$\lambda_{max}(t) = mt + b \quad (3)$$

where m is the slope and b is the intercept.

To evaluate the effect of SIF on the kinetics of NO release, the slopes of the fitted lines were compared. The relative acceleration of the process was defined as the ratio of the slopes for the sample and the control (blank):

$$F_{NO} = \left| \frac{m_{sample}}{m_{blank}} \right| \quad (4)$$

This value is analogous to the ME-NO• factor introduced in [14], Equation (2), and reflects the relative increase (or decrease) in signal output in the presence of nanostructures. The uncertainty in the ratio of rates was calculated using the formula:

$$\sigma_{F_{NO}} = F_{NO} \cdot \sqrt{\left(\frac{\Delta m_{sample}}{\langle m_{sample} \rangle} \right)^2 + \left(\frac{\Delta m_{blank}}{\langle m_{blank} \rangle} \right)^2}, \quad (5)$$

where Δm is the standard error of the slope determined by fitting.

2.6. Singlet Oxygen Detection

Evaluation of the singlet oxygen ($^1O_2$) yield enhanced by plasmonic effects, referred to as the ME- $^1O_2$ Factor, was performed in similar manner. The detection of singlet oxygen was carried out using the probe 1,3-diphenylisobenzofuran (DPBF) [18,19], which exhibits strong fluorescence when excited at a wavelength of 410 nm. Upon interaction with singlet oxygen, DPBF shows a decrease in the fluorescence peak intensity, allowing indirect assessment of the singlet oxygen yield.

The normalized spectrum $\Delta S(\lambda)$ was calculated as follows:

$$\Delta S(\lambda) = \frac{I_{dark}(\lambda) - I_{sample}(\lambda)}{I_{dark}(\lambda) - I_{baseline}(\lambda)}, \quad (6)$$

where $I_{\text{dark}}(\lambda)$ is the fluorescence emission spectrum without irradiation, $I_{\text{sample}}(\lambda)$ is the emission spectrum of the sample on SIF after irradiation, and $I_{\text{baseline}}(\lambda)$ is the baseline emission spectrum (measured for the solvent).

Due to the broad absorption profile of DPBF and the characteristics of its fluorescence excitation, the most sensitive range to changes was found to be between 450 and 480 nm. In this range the normalized spectrum was averaged:

$$\langle \Delta S \rangle = \frac{1}{N} \sum_{\lambda=450}^{480} \Delta S(\lambda) \quad (7)$$

And the standard deviation was also calculated as:

$$\sigma_{\Delta S} = \sqrt{\frac{1}{N-1} \sum_{\lambda=450}^{480} (\Delta S(\lambda) - \langle \Delta S \rangle)^2} \quad (8)$$

To evaluate the effect of SIF, all sample measurements were normalized to the control (blank) glass substrate:

$$F_{\text{O}_2} = \frac{\langle \Delta S_{\text{sample}} \rangle}{\langle \Delta S_{\text{blank}} \rangle} \quad (9)$$

This coefficient reflects the metal-enhanced generation of singlet oxygen and will be referred to as the ME^{-1}O_2 factor. Its uncertainty was calculated using standard error propagation approach:

$$\sigma_{F_{\text{O}_2}} = F_{\text{O}_2} \cdot \sqrt{\left(\frac{\sigma_{\text{sample}}}{\langle \Delta S_{\text{sample}} \rangle} \right)^2 + \left(\frac{\sigma_{\text{blank}}}{\langle \Delta S_{\text{blank}} \rangle} \right)^2} \quad (10)$$

3. Results and Discussion

3.1. Localized Plasmon Resonance of SIF

Silver nanoparticles typically exhibit a dipole plasmon resonance in the 350–400 nm wavelength range. However, to achieve spectral overlap with the absorption band of the employed dye, a plasmon resonance peak within the 450–550 nm range is required. To shift the plasmon resonance accordingly, we utilized silver island films (SIFs) composed of relatively large nanoparticles with high surface coverage.

Figure 1B presents a representative three-dimensional AFM image of the film surface. The dark region at the bottom corresponds to the substrate, while the individual silver nanoparticles appear as round features distributed across the surface. The measured heights of these particles (80–105 nm) closely represent their actual diameters. In contrast, the lateral dimensions observed in the topographic image (170–210 nm) are artificially increased due to the well-known convolution effect between the inclined AFM probe tip and the quasi-spherical nanoparticle surfaces, an artifact commonly encountered in AFM imaging.

Nanoparticles with diameters around 100 nm support not only dipolar but also higher-order plasmonic modes, such as quadrupolar resonances, which contribute to the broad extinction band observed in the visible spectral region [20,21]. Additionally, the particle surface density is relatively high, approximately 20 particles per μm^2 , which promotes interparticle plasmonic coupling. This coupling results in further red-shift the plasmon resonance peak due to collective electromagnetic interactions among neighboring nanoparticles [22,23].

3.2. Plasmonic Nanoparticle Influence Photodissociation and Photobleaching Rate

In the experiment described above, the “sandwich” sample with zero buffer layer thickness “SIF(0 nm)” was irradiated using a 500 nm LED, followed by control measurements of the fluorescence spectra of the clean glass substrates. Figure 5A shows the fluorescence emission spectra of the samples. The green arrow in the graph indicates the shift in the fluorescence maximum in the sample with the SIF, which occurs several times faster than in the control sample (blue line). Moreover, the final fluorescence amplitude in the presence of SIF approximately four times higher, indicating suppressed photobleaching compared to the control. To test the hypothesis of a simple acceleration of the reaction kinetics, a control experiment was conducted with varying LED power (Figure 5B,C). Although increasing the diode current leads to a proportional acceleration of the reaction, the rate of photobleaching remains unchanged. This indicates that the observed effect is not merely due to an increased absorbed energy, but may be a selective influence on dye molecules located in close proximity to the silver islands.

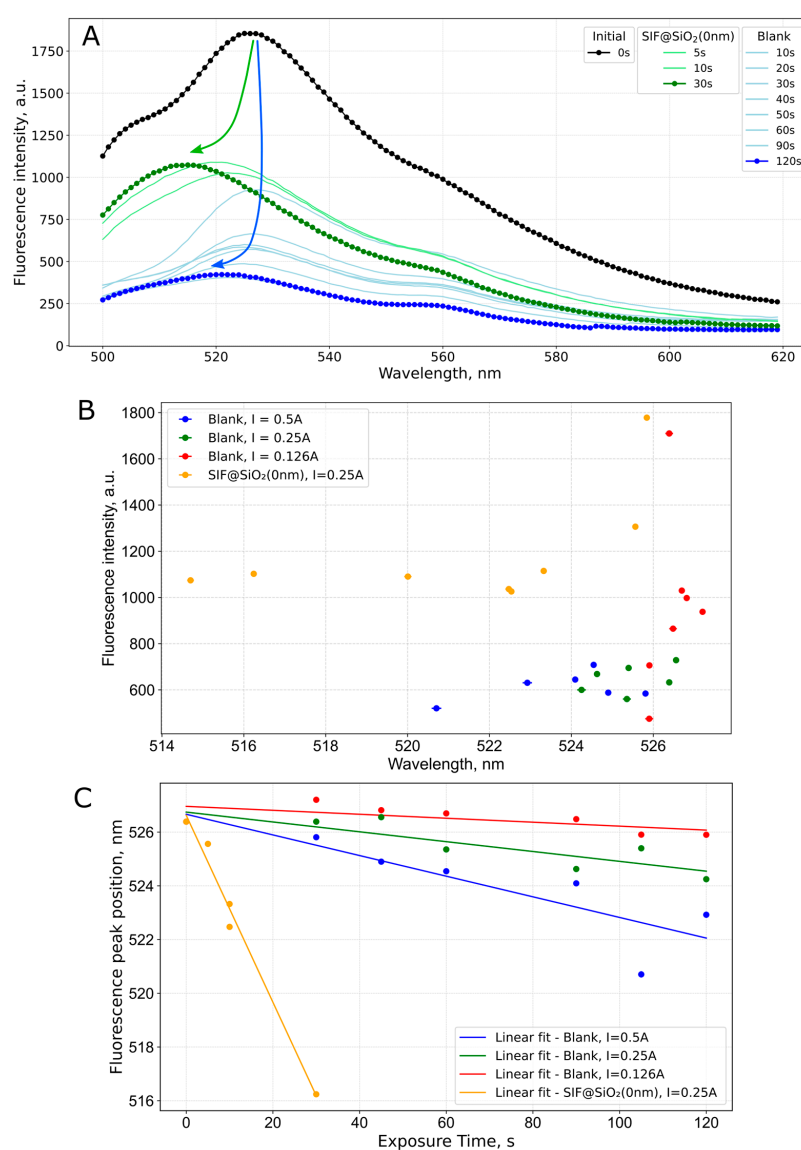


Figure 5. Effect of SIFs on the NO photorelease and photobleaching of the dye. (A). Fluorescence emission spectra after the photolysis. (B). Intensity and wavelength at the maxima of the emission spectra. LED current I is shown in the legend. (C). Spectral shift versus the irradiation time and linear fit.

3.3. Photolysis at Non-Resonant Wavelength

To further demonstrate plasmon-enhanced NO release, a comparative experiment was conducted using excitation at 405 nm, a wavelength outside the plasmon resonance range of the silver island film “SIF(0 nm)”. Figure 6 shows the temporal evolution of the fluorescence peak position for both samples with the SIF and the control samples, under excitation at 500 nm (in resonance) and 400 nm (out of resonance). Analysis of the kinetic curves using linear approximation (the ME-NO-Factor was calculated according to the method described in Section 2) revealed a significant difference in NO generation efficiency: under resonant excitation at 500 nm, the NO release rate in the presence of plasmonic structures exceeded the control by a factor of 7 ± 1.3 , whereas under 400 nm excitation, the enhancement was only 3 ± 0.9 .

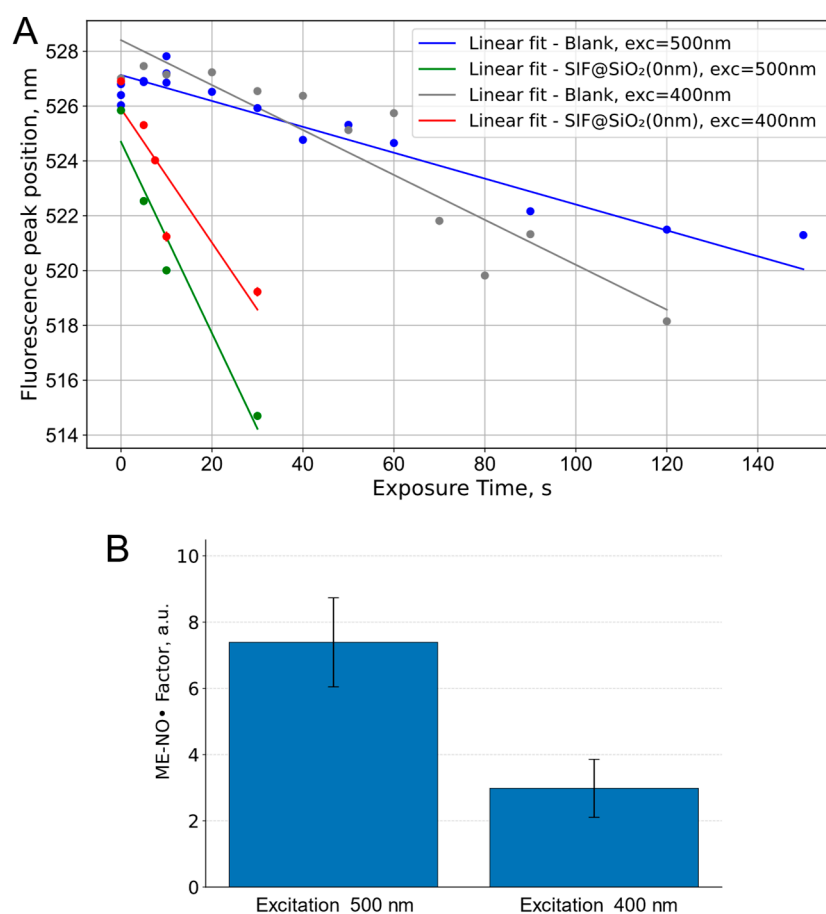


Figure 6. (A). Spectral shift versus the irradiation time for two different wavelengths of irradiation. (B). Enhancement factor of NO release under irradiation with green (500 nm) and violet (405 nm) LEDs for SIF with zero buffer layer thickness.

Comparative analysis of NO generation efficiency showed that the relative reaction rate at 500 nm was 2.5 ± 0.9 times higher than that at 400 nm. This selective enhancement, observed exclusively under plasmon resonance conditions, clearly indicates the pivotal role of localized surface plasmons in the studied process.

3.4. Influence of the Buffer Layer

To unambiguously confirm the plasmonic nature of the observed effect and exclude the contribution of chemical interaction with silver, an additional control experiment was conducted. We investigated a series of SIF samples exhibiting similar extinction spectra (Figure 7A) but differing in the thickness of the SiO₂ buffer layer (0.5, 2, and 20 nm). This

approach allows variation in the distance between the dye molecules and the silver islands while preserving the plasmonic characteristics of the system.

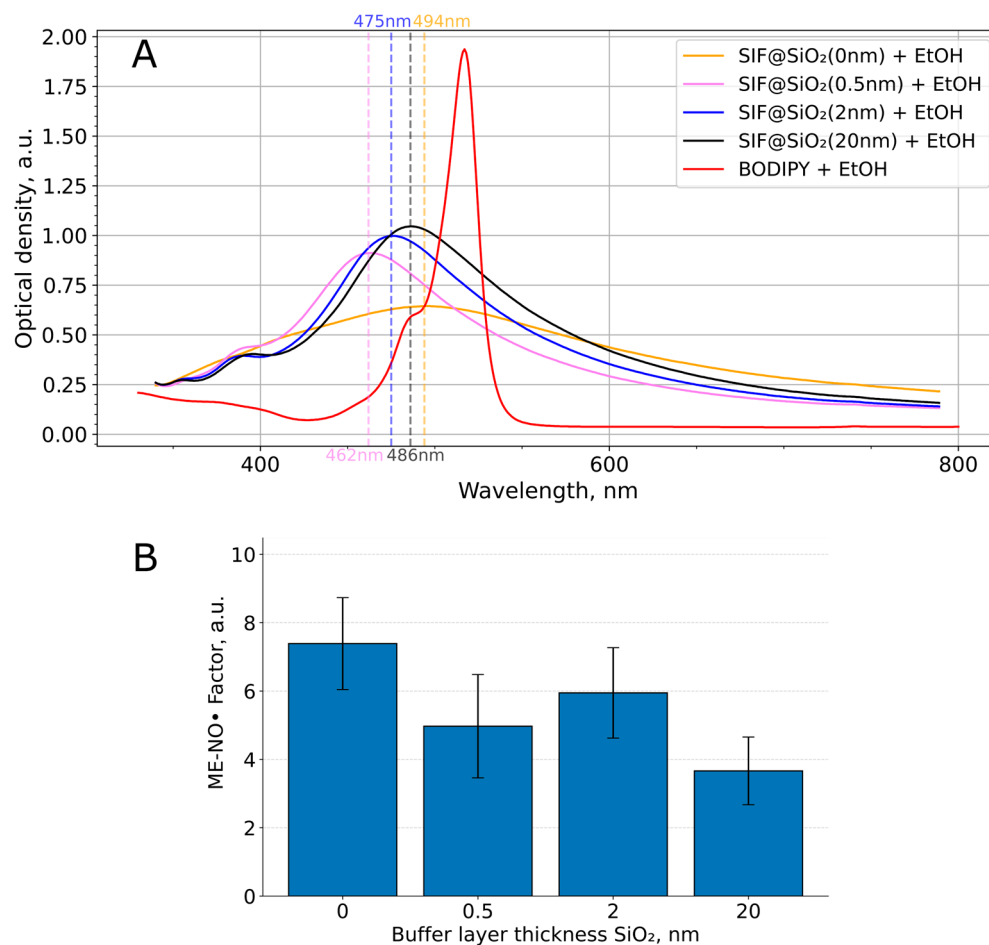


Figure 7. (A): Optical density spectra of silver island films with different SiO₂ buffer layer thicknesses in a cuvette with ethanol; the absorption spectrum of BODIPY N1 in ethanol is shown by the red line. (B): ME-NO-Factor under green LED (500 nm) irradiation for SIF samples with varying buffer layer thickness.

The results of the comparative analysis of four silver island films with different SiO₂ buffer layer thicknesses are presented in Figure 7B. The bar chart shows the dependence of the NO release enhancement factor (ME-NO-Factor) on buffer layer thickness under excitation with a 500 nm LED.

The diagram shows the dependence of the NO release rate on the buffer layer thickness. As the thickness increases, a decrease in the relative rate of NO release is observed. However, it is important to note that increasing the buffer layer thickness is also accompanied by a shift in the plasmon resonance toward longer wavelengths. Therefore, considering the effect of thickness alone would be incorrect: the position of the plasmon resonance relative to the dye absorption maximum also plays a crucial role.

It is worth noting that the optical density spectra of the samples without buffer layer and with a 20 nm layer are quite similar as their plasmon resonance peaks differ by less than 10 nm. This suggests that the observed difference in NO release may indeed be attributed to the change in buffer layer thickness.

To further verify these conclusions, two additional samples with silver island films and buffer layer thicknesses of 0.5 nm and 2 nm were analyzed. In these cases, a clear interplay between two factors is observed: the degree of overlap between the plasmon resonance

and the dye absorption spectrum, and the buffer layer thickness. This may explain why the relative NO release rate differs by only ~15%. For example, the SIF with a 2 nm SiO₂ layer (four times thicker than the 0.5 nm sample) exhibits a 13 nm red shift in the plasmon resonance, resulting in better overlap with the dye's absorption. This confirms that optimal spectral overlap is at least as important for the photodissociation process as the buffer layer thickness itself.

3.5. Singlet Oxygen Generation

Next, we evaluated the singlet oxygen (¹O₂) yield enhanced by plasmonic effects—the so-called ME-¹O₂ Factor—in our system. DPBF, a probe exhibiting intense fluorescence upon excitation at 410 nm, was used for singlet oxygen detection. Figure 8A shows the decrease in DPBF fluorescence intensity, allowing an indirect assessment of singlet oxygen production.

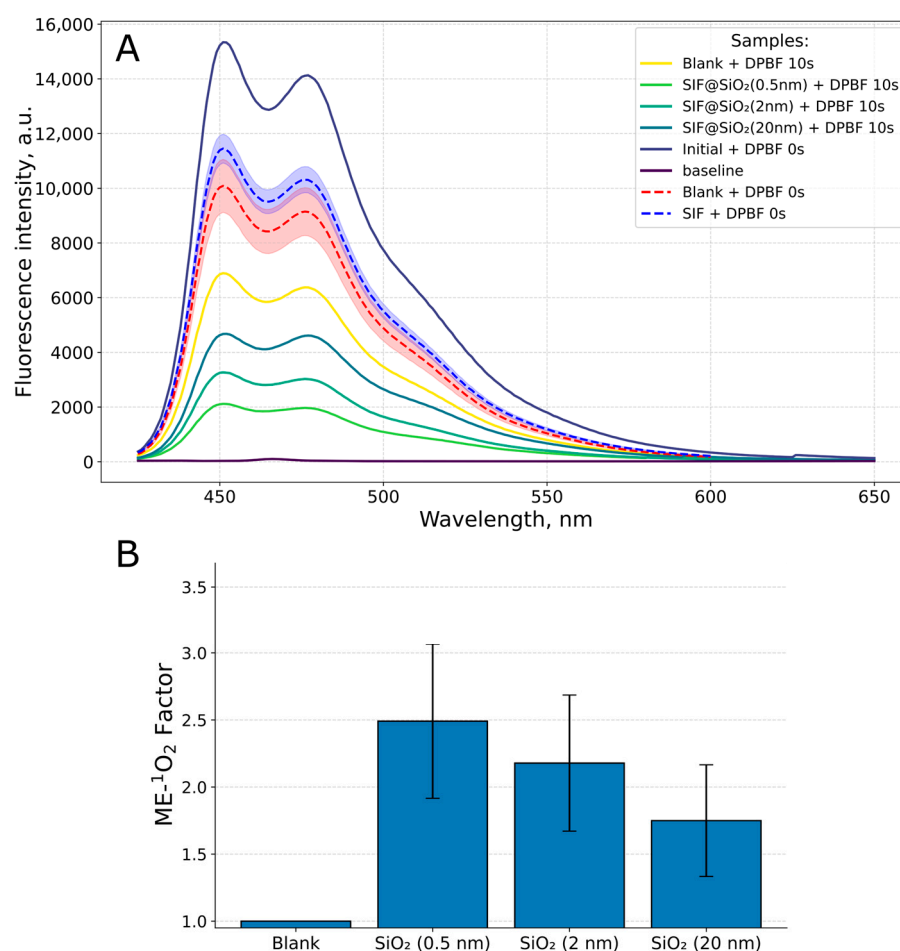


Figure 8. (A): Fluorescence emission spectra of DPBF probe after irradiation on different SIF and control samples. (B): ME-¹O₂ Factor under green LED (500 nm) irradiation for SIF samples with varying buffer layer thickness. Initial refers to the original signal in the cuvette with ethanol.

Only silver island films with nonzero buffer layer thicknesses were used in the experiment, since the probe may chemically react with silver, and direct contact leads to distorted results. Samples were irradiated with a green LED at 500 nm for 10 s. The resulting fluorescence spectra were processed according to the methodology described in Section 2.

The results are presented as a bar chart (Figure 8B). It shows that decreasing the buffer layer thickness increases the singlet oxygen yield up to 2.5 times compared to the control sample. These data are consistent with the findings of studies [11,12], which also reported plasmon-enhanced singlet oxygen generation.

4. Conclusions

In this study we investigated hybrid nanophotonic systems composed of photochemically active BODIPY-based NO donors and SIFs to assess the influence of localized plasmonic effects on nonradiative relaxation pathways and the generation of reactive oxygen species. The results demonstrated that plasmon resonance induced by metallic nanoparticles significantly accelerates the photodissociation process and enhances NO yield. In particular, excitation at 500 nm led to an up to 7-fold increase in NO release compared to the control sample.

Experiments varying the thickness of the SiO₂ buffer layer revealed two key factors determining the efficiency of the photochemical processes: the degree of overlap between the dye absorption spectrum and the plasmon resonance, and the distance between the molecule and the nanoparticle. Increasing the buffer layer thickness reduced NO generation efficiency, consistent with the decrease in the electromagnetic field near the dye as it moves away from the metal surface. Conversely, closer spectral overlap between the plasmon resonance peak and the dye absorption enhanced NO generation. Thus, the observed enhancement of NO generation can be directly linked to resonant plasmon excitation.

Additionally, singlet oxygen generation was shown to increase by more than 2.5 times as the buffer layer thickness decreased. Although absolute values for ¹O₂ were determined qualitatively due to the characteristics of the detection method (using DPBF), the overall trend aligns well with the NO yield results and with the literature.

Given the demonstrated ability of this nanoplatform to controllably enhance both NO and singlet oxygen generation, it holds strong potential for biomedical applications. However, these applications require reformulation of the platform into biocompatible system, in vitro studies on established cancer cell lines, and in vivo validation in xenograft tumor models that allow assessment of tumor targeting efficiency and therapeutic outcomes. At the same time, from a fundamental perspective, this hybrid platform provides a useful model for studying plasmon–molecule interactions and controlled modulation of nonradiative processes. Future research may further advance this approach toward more complex hybrid systems, such as nanoparticle–dye constructs with embedded molecules in protective shells, which could facilitate efficient intracellular delivery and activation.

In summary, these findings confirm the possibility of controlled enhancement of relaxation and photochemical processes in organic sensitizer molecules via localized plasmon resonances. Such hybrid systems represent a promising platform for developing targeted, selective, and highly efficient next-generation phototherapeutic approaches, including therapies for oncological and inflammatory diseases.

Author Contributions: Conceptualization, N.A.V.; methodology, A.E.M.; software, D.V.S.; investigation, D.V.S., P.V.G. and A.E.M.; resources, I.A.G., M.A.P. and A.Y.V.; writing—original draft preparation, D.V.S.; writing—review and editing, P.V.G. and A.E.M. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Abbreviations

The following abbreviations are used in this manuscript:

NO	Nitric oxide
ROS	Reactive oxygen species
PDT	Photodynamic therapy
SIF	Silver island films
$^1\text{O}_2$	Singlet oxygen
BODIPY	Boron-dipyrromethene
AFM	Atomic force microscopy
LED	Light emitting diode
DPBF	1,3-diphenylisobenzofuran
DAR-2	5,6-diamino-rhodamine B

Appendix A

One common method for detecting NO involves using fluorescent molecular traps such as DAR-2. Upon reacting with NO, DAR-2 exhibits an increase in fluorescence intensity. This approach has proven effective in our previous studies. However, in the current experiment, no statistically significant difference in fluorescence intensity was observed between samples with silver island films (SIFs), both with and without SiO_2 coatings, and control samples on bare glass (Figure A1).

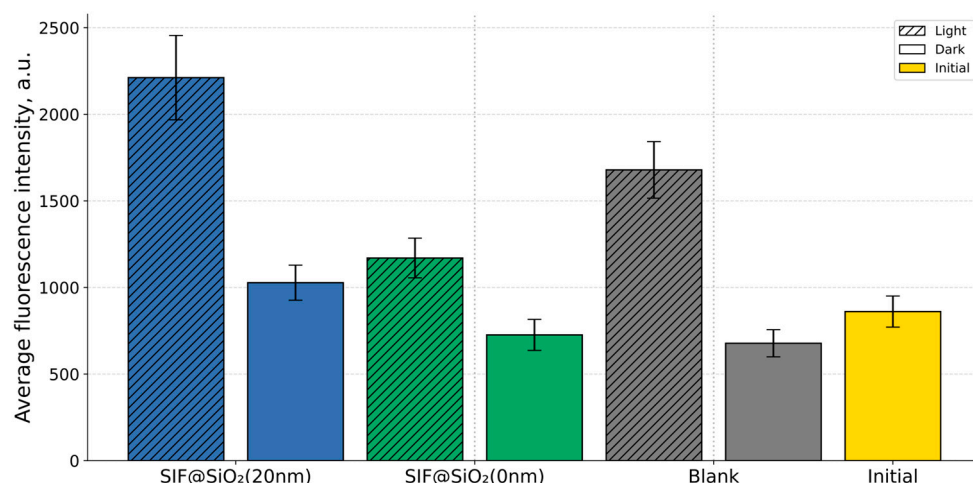


Figure A1. Average fluorescence intensity in the 555–580 nm range for samples with silver island films SIF (20 nm), SIF (0 nm), and for bare glass (Blank). Initial refers to the original signal in the cuvette with ethanol.

We hypothesize that the DAR-2 probe is reactive toward silver, which may explain the decrease in fluorescence intensity observed even in samples with a 20 nm thick silver film. It is important to note that samples without a buffer layer were pre-treated with sodium citrate passivation to minimize chemical pathways of photodissociation. Nevertheless, the DAR-2 probe appeared to be partially inactivated under these experimental conditions.

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